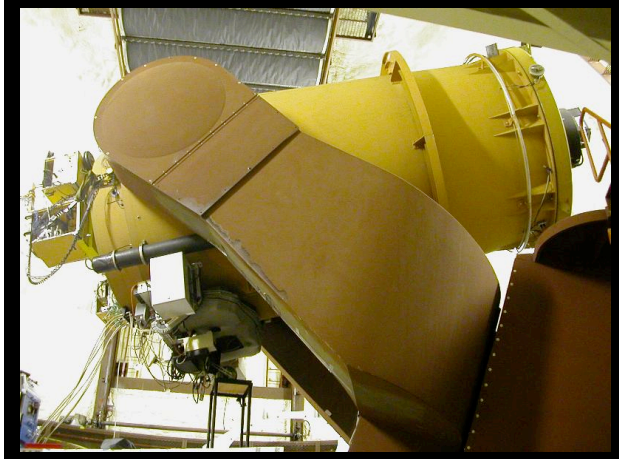

The Nearby
Supernova Factory



LBL
G. Aldering
M. Childress
S. Loken
S. Perlmutter

NERSC
C. Aragon
P. Nugent
A. Pinar
R. Thomas

SSL
S. Bongard
A. McLeod
K. Runge

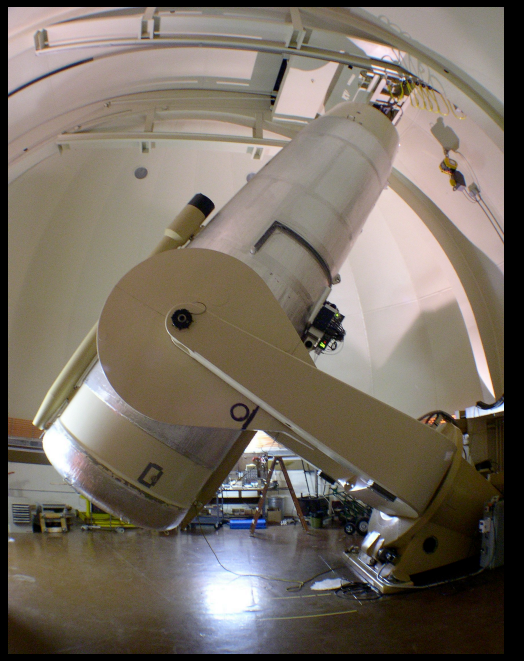
Yale
C. Baltay
D. Rabinowitz
R. Scalzo

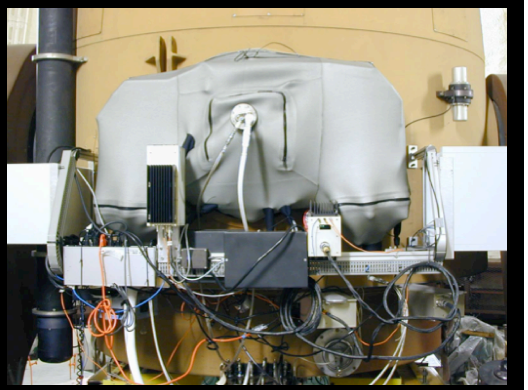
CRAL
E. Pecontal
G. Rigaudier

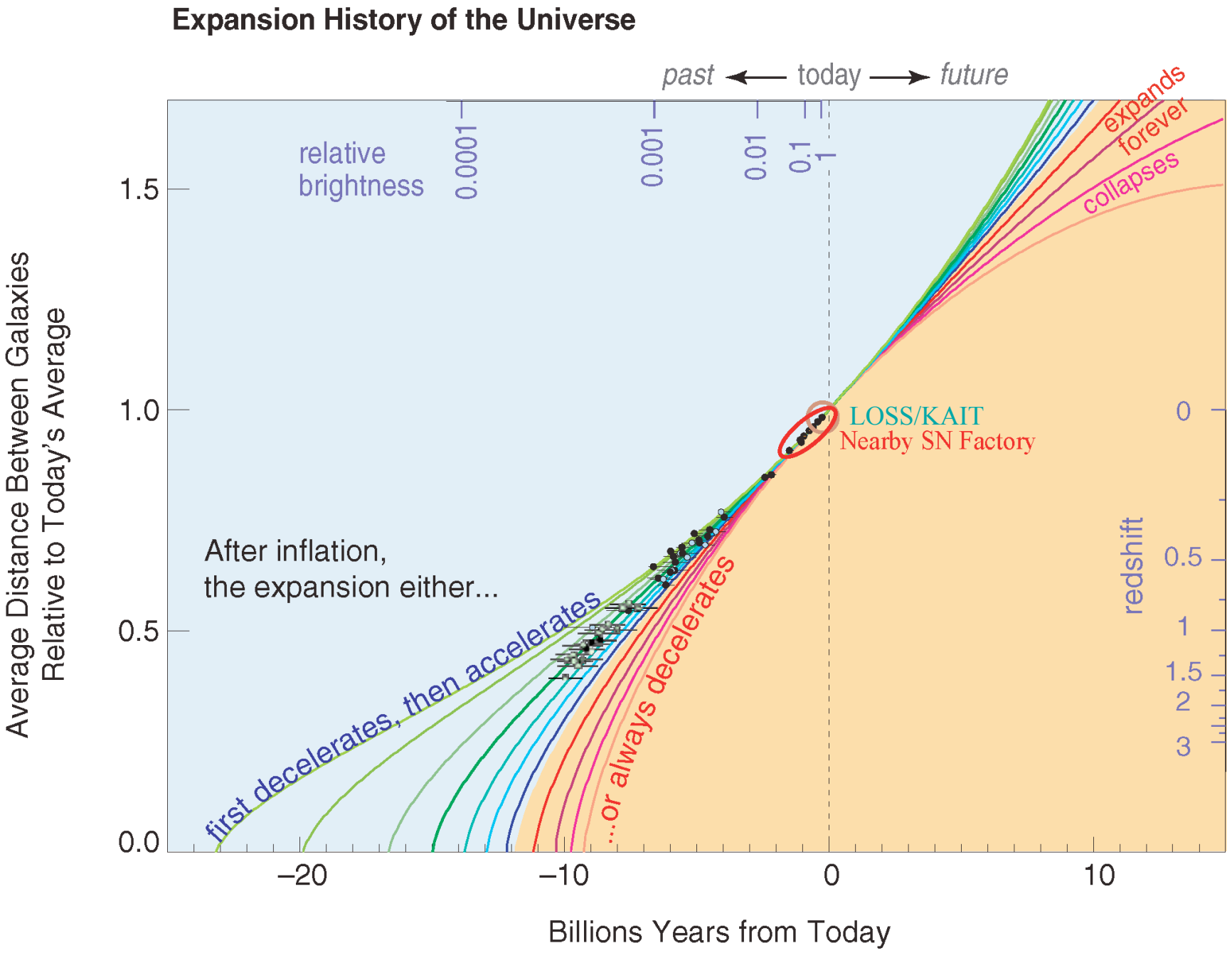
IPNL
C. Buton
Y. Copin
E. Gangler
G. Smadja

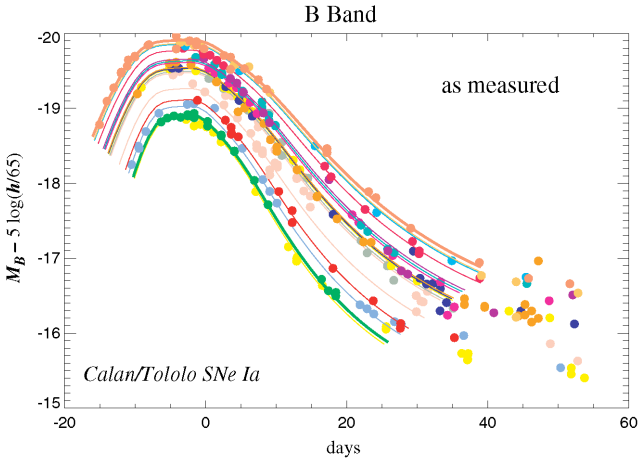
LPNHE
P. Antilogus
S. Bailey
R. Pain
R. Pereira
P. Ripoche
C. Wu

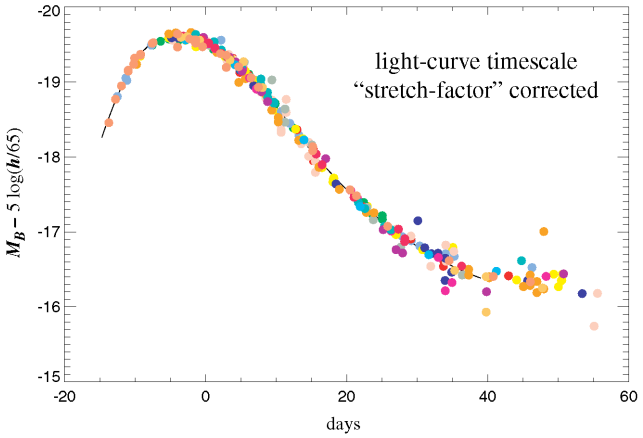
CPPM
C. Tao

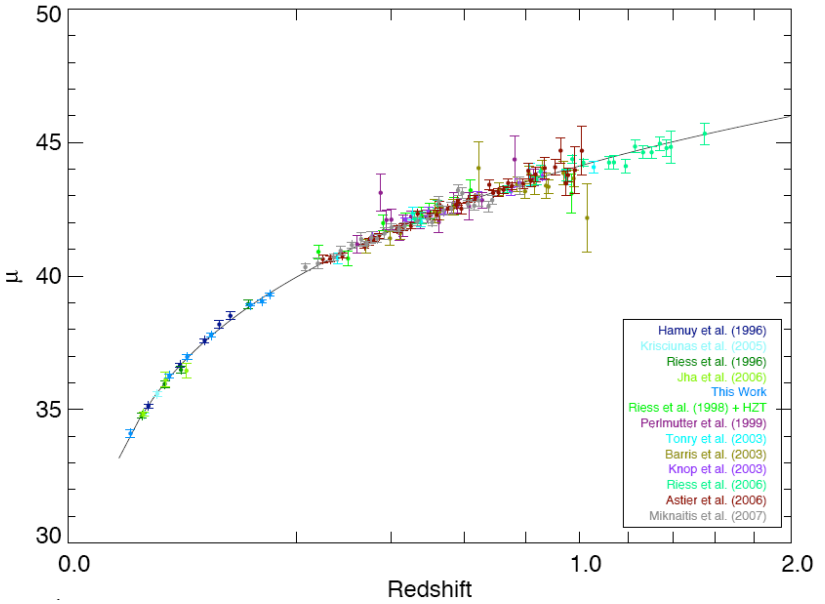


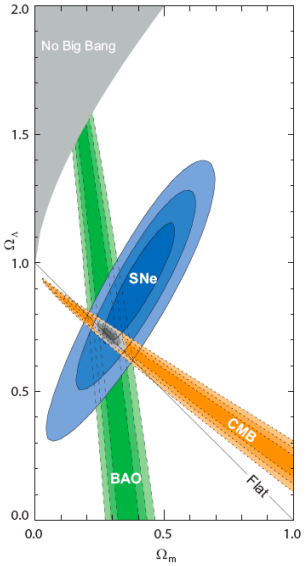


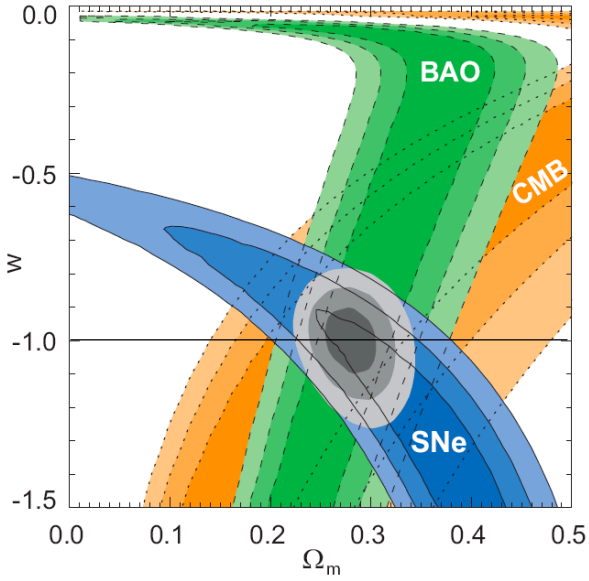

Expansion History of the Universe
past
today
future
relative brightness
0.0001
0.001
0.01
0.1
1
expands forever
collapses
LOSS/KAIT
Nearby SN Factory
redshift
0
0.5
1
1.5
2
3
After inflation,
the expansion either...
first decelerates, then accelerates
...or always decelerates
Average Distance Between Galaxies
Relative to Today's Average
0.0
0.5
1.0
1.5
–20
–10
0
10
Billions Years from Today





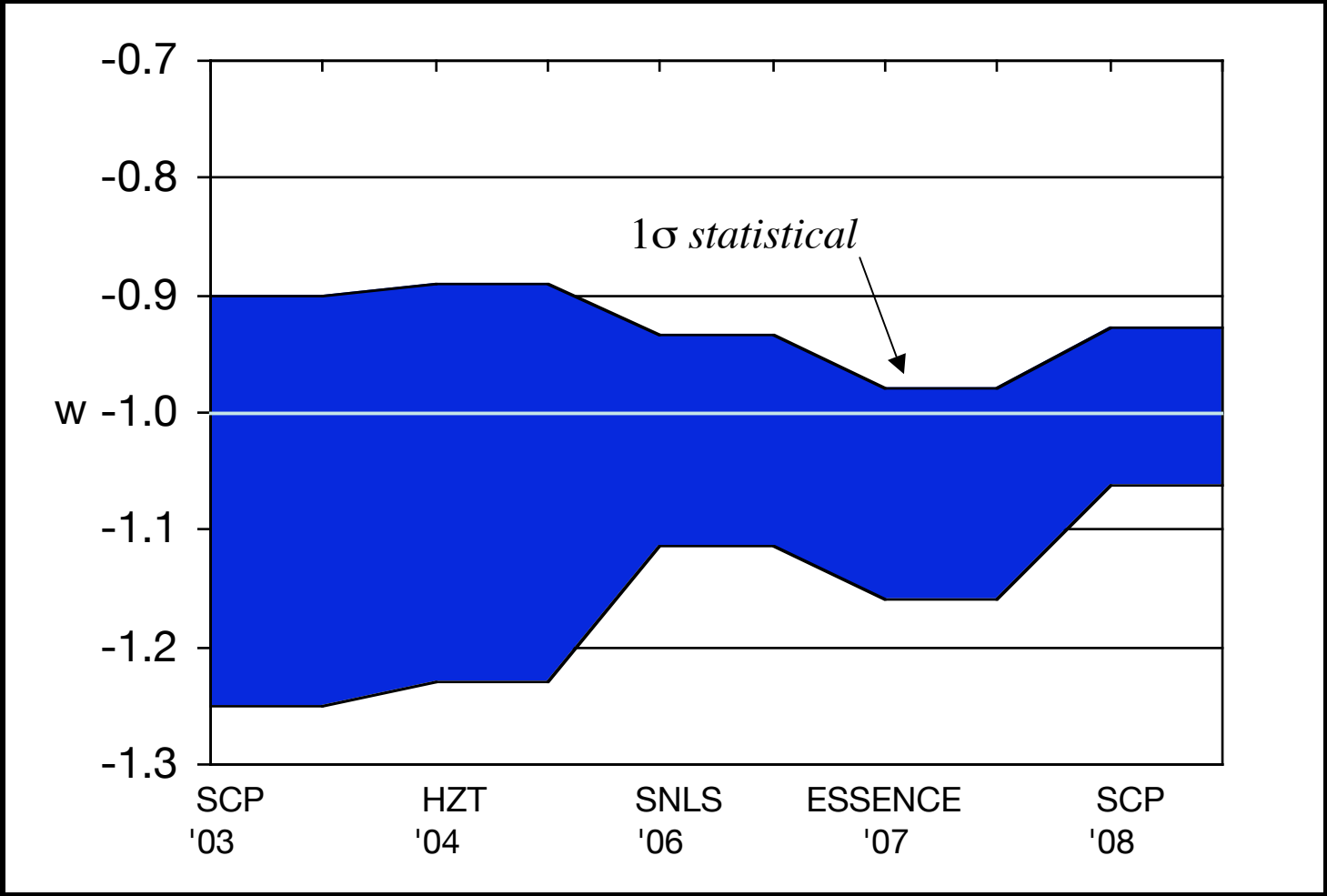






Kowalski *et al.* 2008 (SCP)

Progress on Constant w



Uncertainty & Bias

Sources of Increased μ Dispersion

Source	σ_μ
Flat-fielding	0.01
Focal plane PSF	0.02
Field-field zero point	0.01
Image subtraction	0.01
Subtotal (quadrature sum)	0.026
Gravitational lensing	0.04
Total (quadrature sum)	0.05

Kowalski *et al.* 2008 (SCP)

Source	common (mag)	sample-dependent (mag)
$\alpha\&\beta$ correction	0.015	-
Contamination	-	0.015
Lightcurve model	0.028	-
Zero point	0.021	0.021
Malmquist bias	-	0.020
Gravitational lensing	-	0.008*
Galactic extinction normalization	0.013	-
Total in mag	$\Delta M = 0.040$	$\Delta M_i = 0.033$

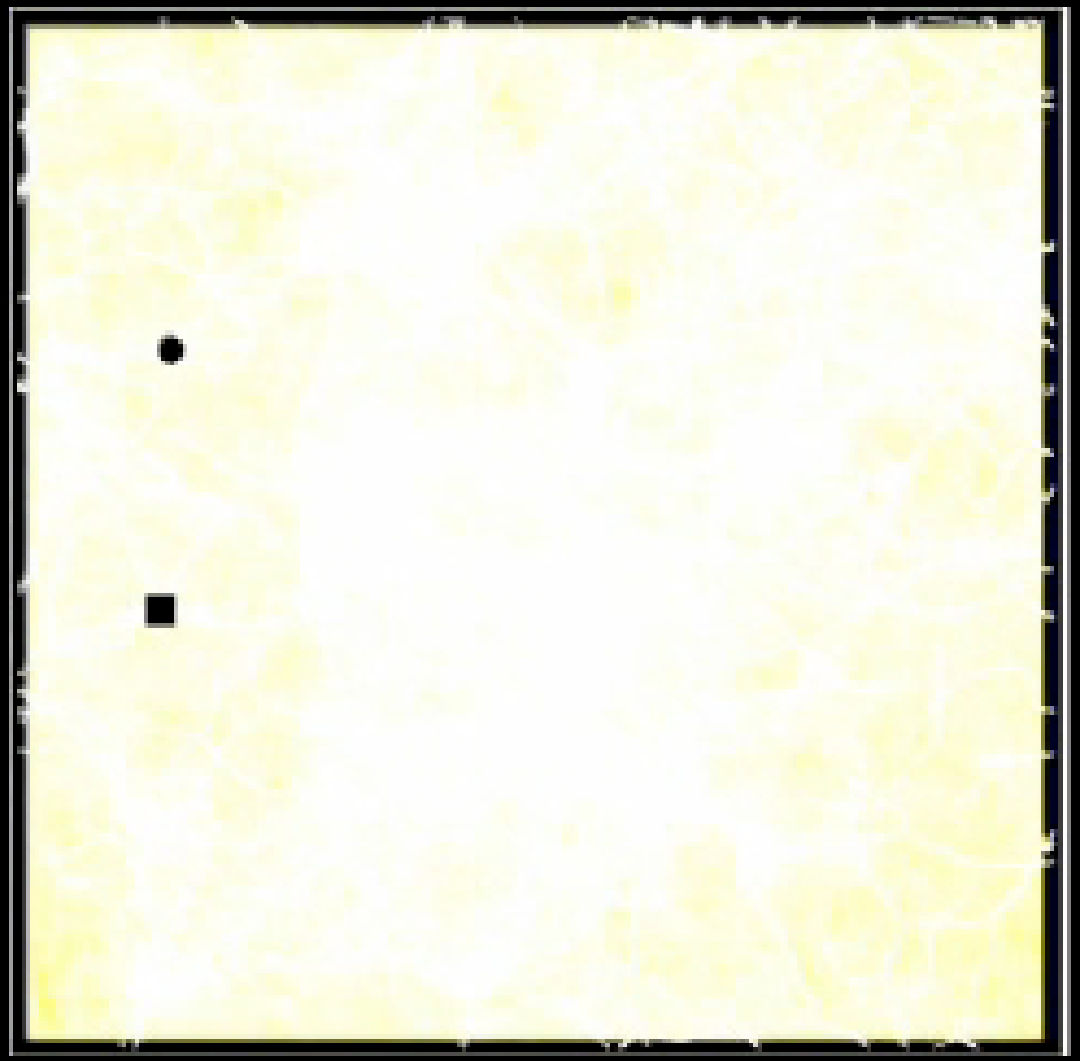
Wood-Vasey *et al.* 2007 (ESSENCE)

TABLE 7

Potential Sources of Systematic Error on the Measurement of w

Source	dw/dx	Δx	Δ_w	Notes
Photometric errors from astrometric uncertainties of faint objects	1/mag	0.005 mag	0.005	
Bias in differential image photometry	0.5/mag	0.002 mag	0.001	
CCD linearity	1/mag	0.005 mag	0.005	
Photometric zero-point differences in R, I	2/mag	0.02 mag	0.04	
Zero-point offset between low and high z	1/mag	0.02 mag	0.02	
K-corrections	0.5/mag	0.01 mag	0.005	
Filter passband structure	0/mag	0.001 mag	0	
Galactic extinction	1/mag	0.01 mag	0.01	
Host galaxy R_V	$0.02/R_V$	0.5	0.01	"glosz"
Host galaxy extinction treatment	0.08	Prior choice	0.08	Different priors
Intrinsic color of SNe Ia	3/mag	0.02 mag	0.06	Interacts strongly with prior
Malmquist bias/selection effects	0.7/mag	0.03 mag	0.02	"glosz"
SN Ia evolution	1/mag	0.02 mag	0.02	
Hubble bubble	$3/\delta H_{\rm effective}$	0.02	0.06	
Gravitational lensing	$1/\sqrt{N}$/mag	0.01 mag	<0.001	Holz & Linder (2005)
Gray dust	1/mag	0.01 mag	0.01	
Subtotal without extinction+color	...	...	0.082	
Total	...	...	0.13	
Joint ESSENCE+SNLS comparison	...	...	0.02	Photometric system
Joint ESSENCE+SNLS total	...	...	0.13	

Peculiar Velocities & Bulk Flows



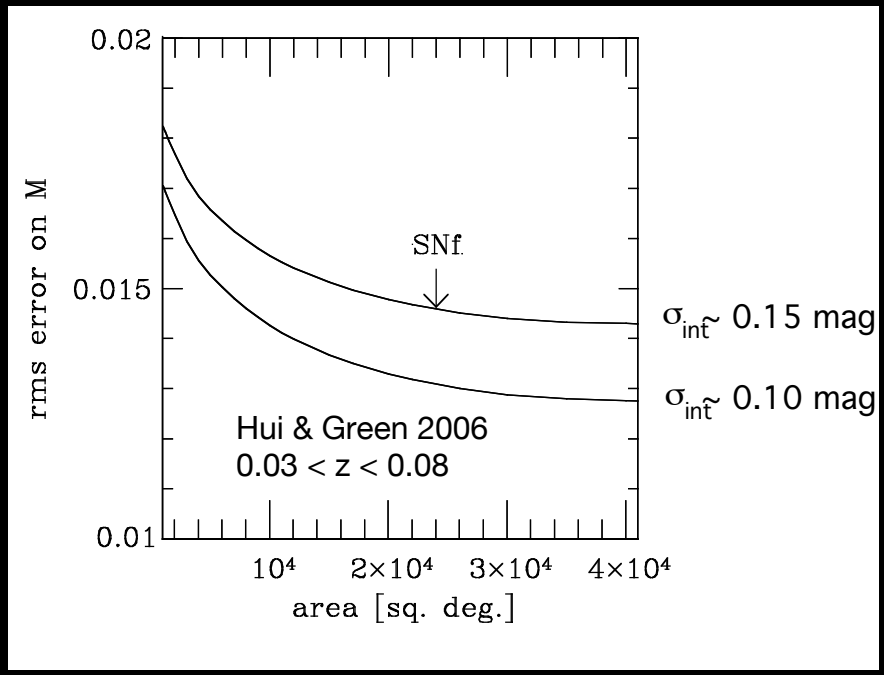
Tully *et al* 2008

Peculiar Velocities & Bulk Flows

Systematic floor ($\sigma_{BF} \sim \sigma_{stat}$) reached for:

20000 sq deg and z < 0.03 and
18 SNe if σ_{int} ~ 0.10 mag or
48 SNe if σ_{int} ~ 0.17 mag

20000 sq deg and 0.03 < z < 0.08 and
165 SNe if σ_{int} ~ 0.10 mag or
500 SNe if σ_{int} ~ 0.17 mag

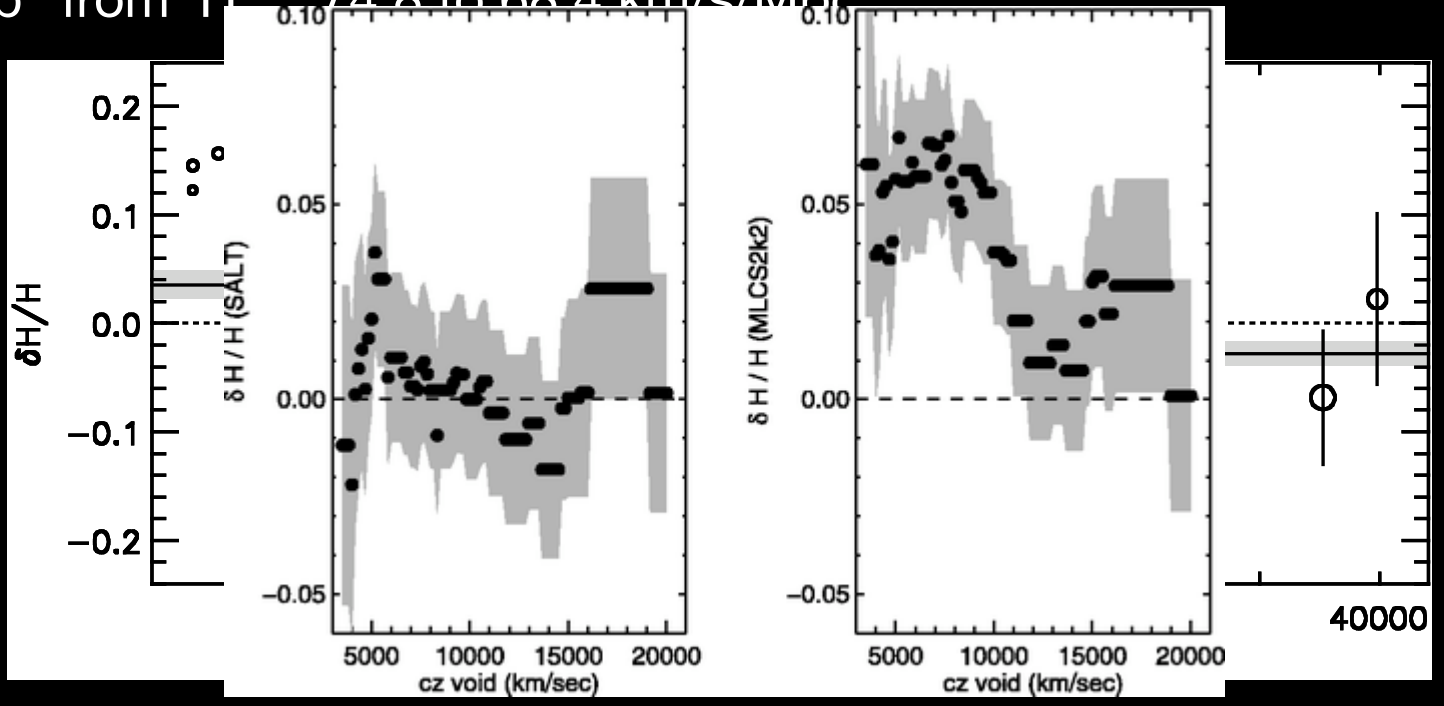


Correctable? Perhaps.
- SFI++ good to 66 km/s (stat; Feldman & Watkins 2008)
- Must absorb galaxy calibration errors

The CfA "Hubble Bubble"
Bulk Flows? SCP Hubble? SN Colors?

Zehavi et al., 1998
Jha et al. 2007 - evidence even stronger
Conley et al 2007 - depends on color correction

"Drop" from H_0 = 74.8 to 68.4 km/s/Mpc



Experimental Goals

Anchoring the Hubble Diagram

$$\sigma_{ZP}^2 \sim \frac{\sigma_{peak}^2 + \sigma_{int}^2 + \left(2\left(\frac{300\ km/s}{cz}\right)\right)^2}{N-2} + \sigma_{BF}^2 + \sigma_{Kcor}^2 + \sigma_{Scor}^2 + \sigma_{Cal}^2$$

… without getting tangled in dark energy

$$\sigma_{w\Omega_m} \sim \frac{3}{4} z \left(\left((1-\Omega_m)^2 \sigma_{w_o}^2 + w_o^2 \sigma_{\Omega_m}^2 \right) \right)^{1/2}$$

Peering inside the Intrinsic Dispersion

$$\sigma_L^2 \sim \frac{\sigma_{peak}^2 + \left(2\left(\frac{300\ km/s}{cz}\right)\right)^2}{N-20} + \sigma_{Kcor}^2 + \sigma_{Scor}^2$$

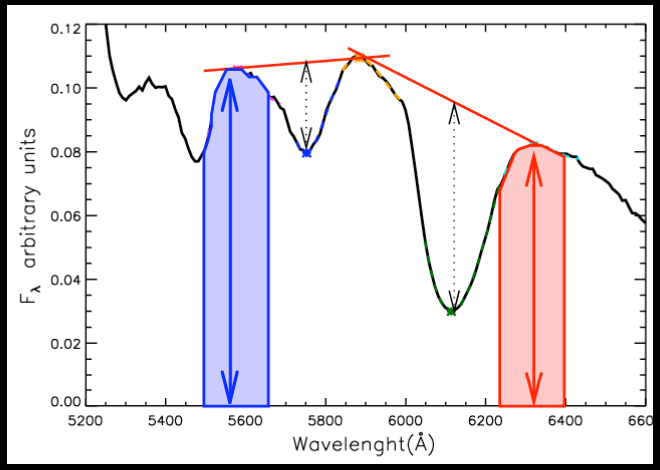
Just a guess!

… with some “Rosetta Stone” supernovae thrown in:

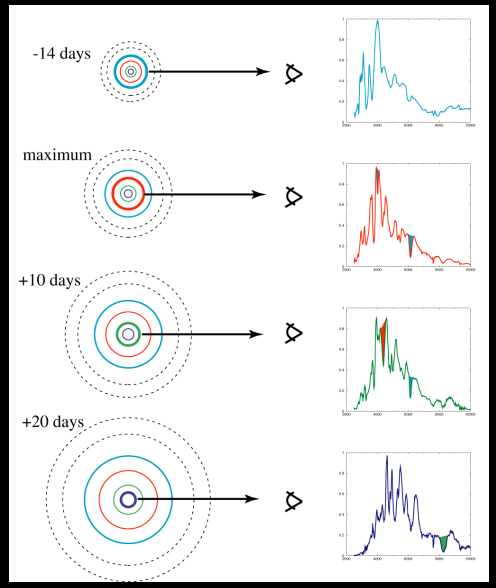
SN2002cx, SN2002ic, SN2005gj, 03D3bb, SN2006D, SNF20070825-001

New Insights from Spectroscopy

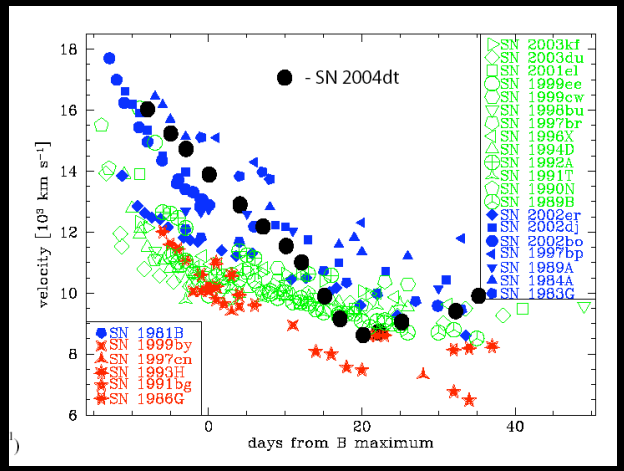
Luminosity Indicators



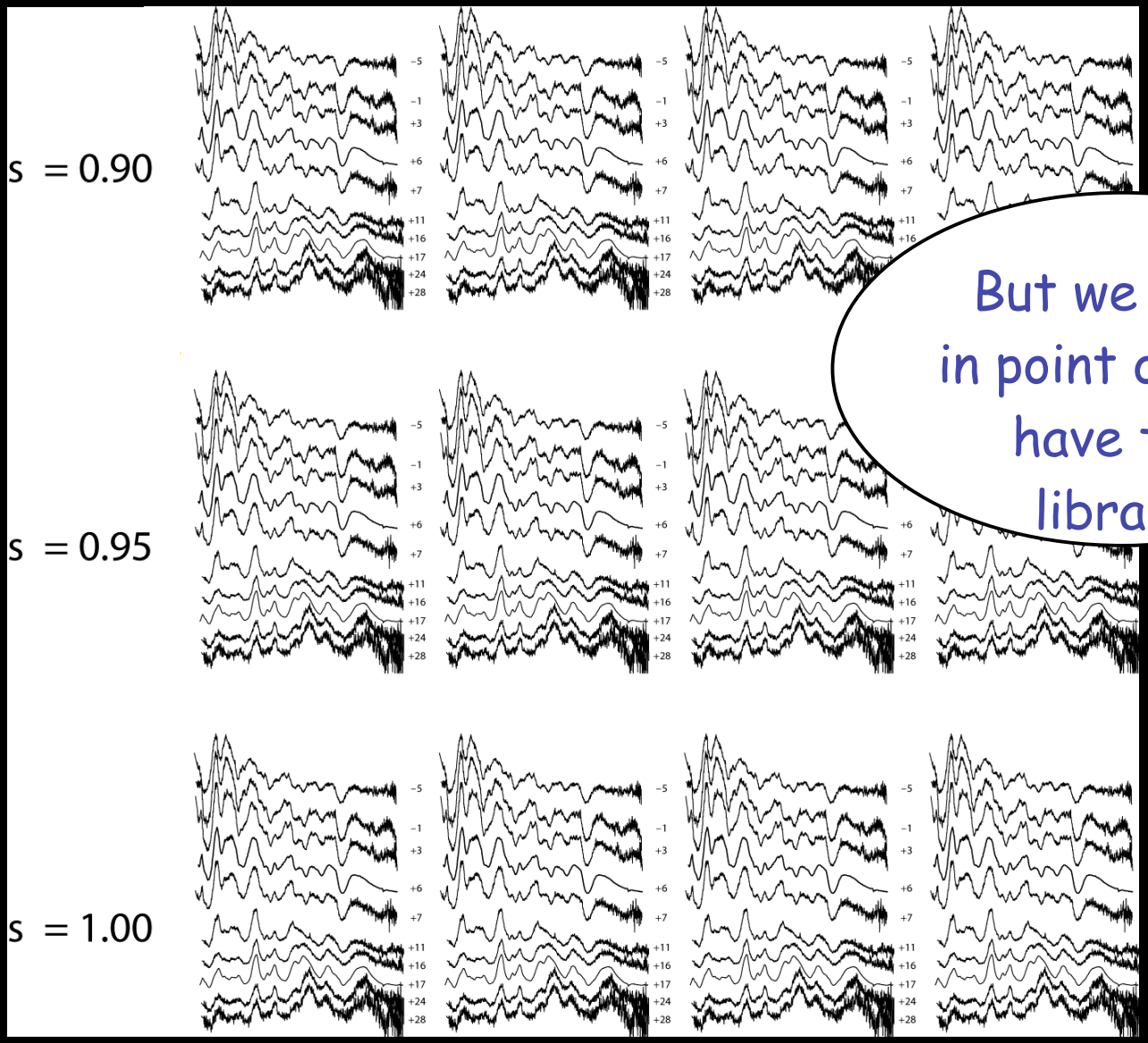
Abundance Tomography



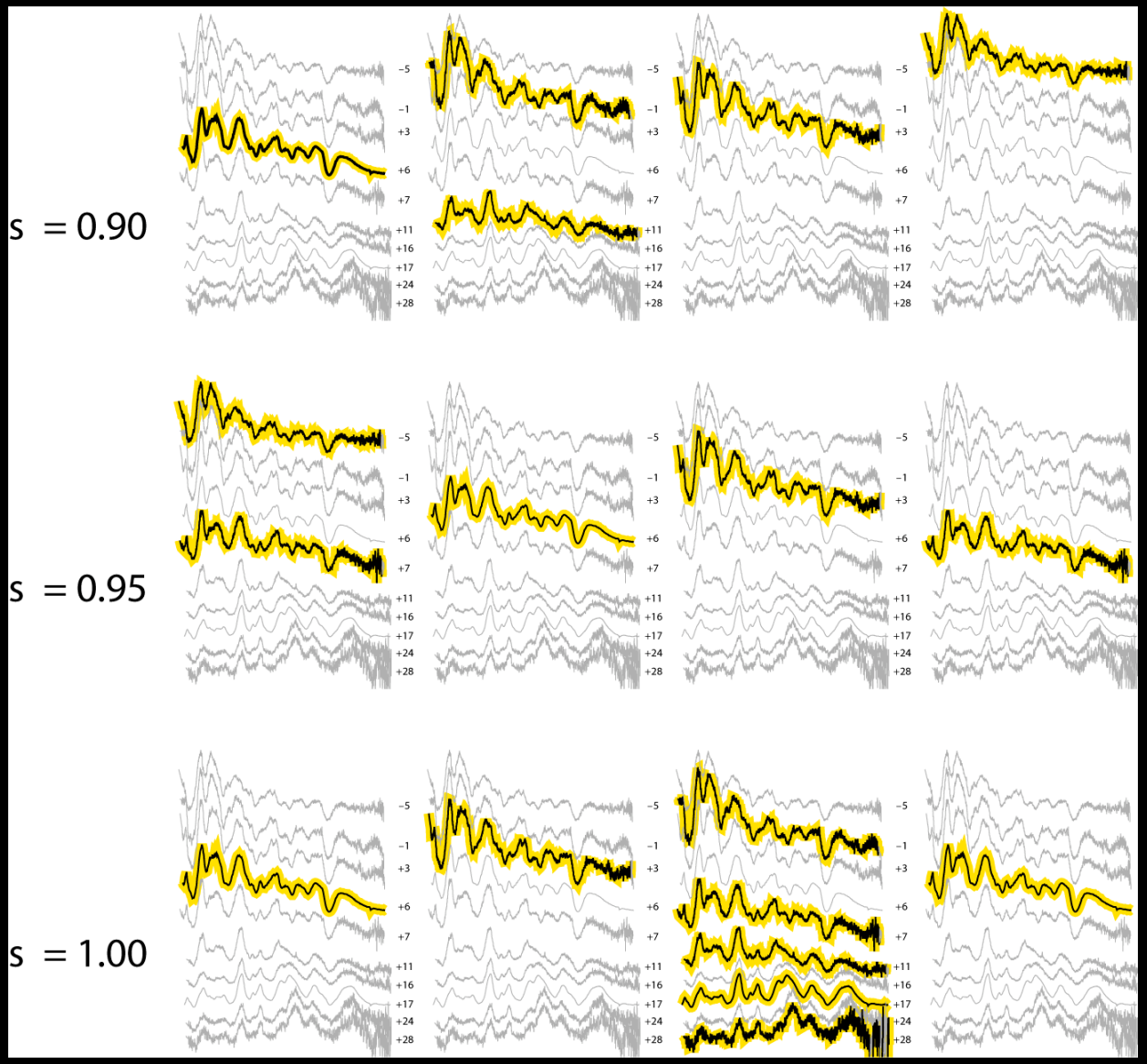
Kinematics



Goal: Library of Spectral Time Series



Reality: Library of Spectral Time Series



A New Paradigm

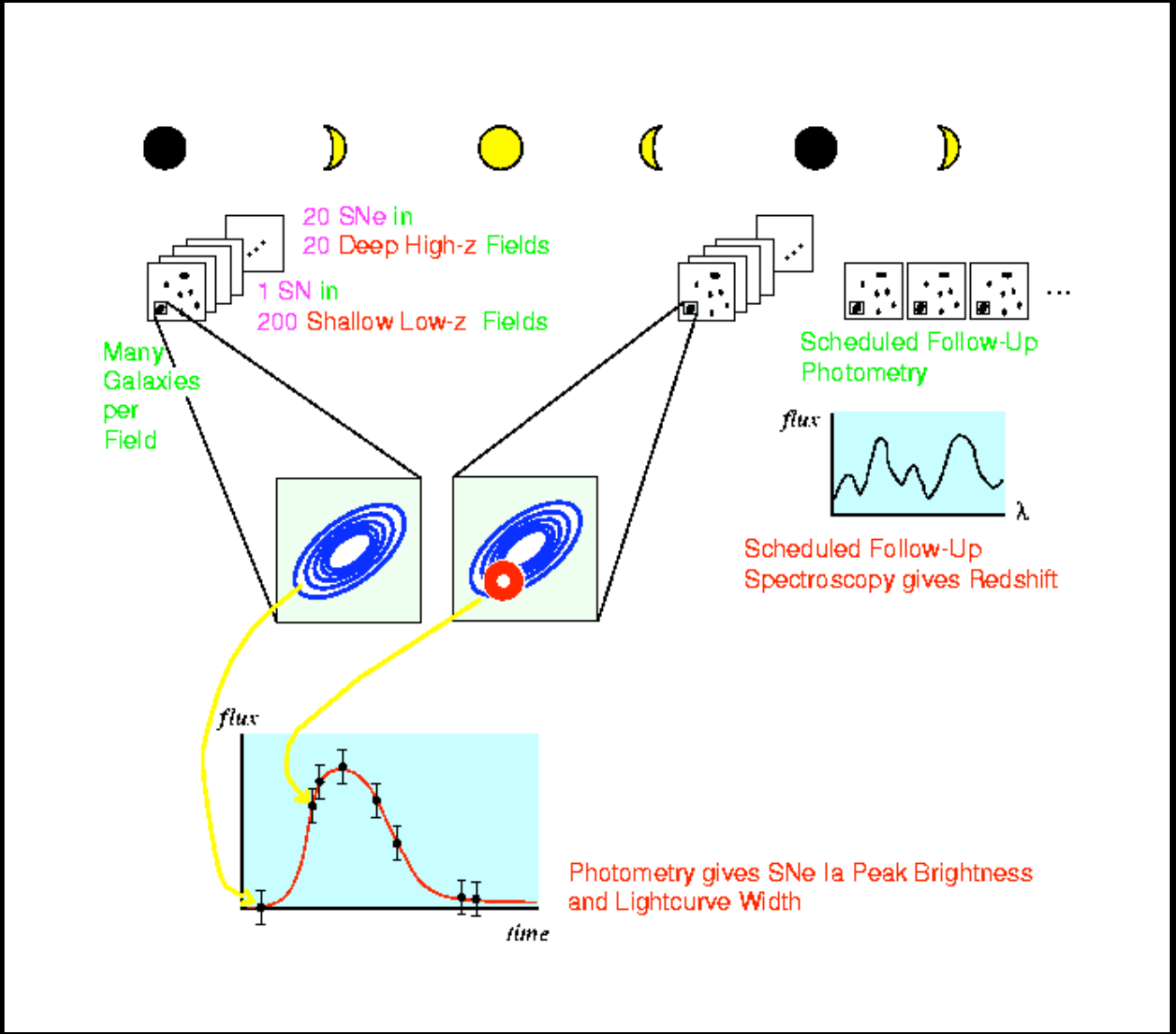
- Search at low redshift just like at high redshift
  - boost discovery rate
  - wide-field, impartial to presence of an associated galaxy
  - find better analogs to high-redshift environment
  - find SNe at earlier lightcurve phase
  - ability to simulate selection effects

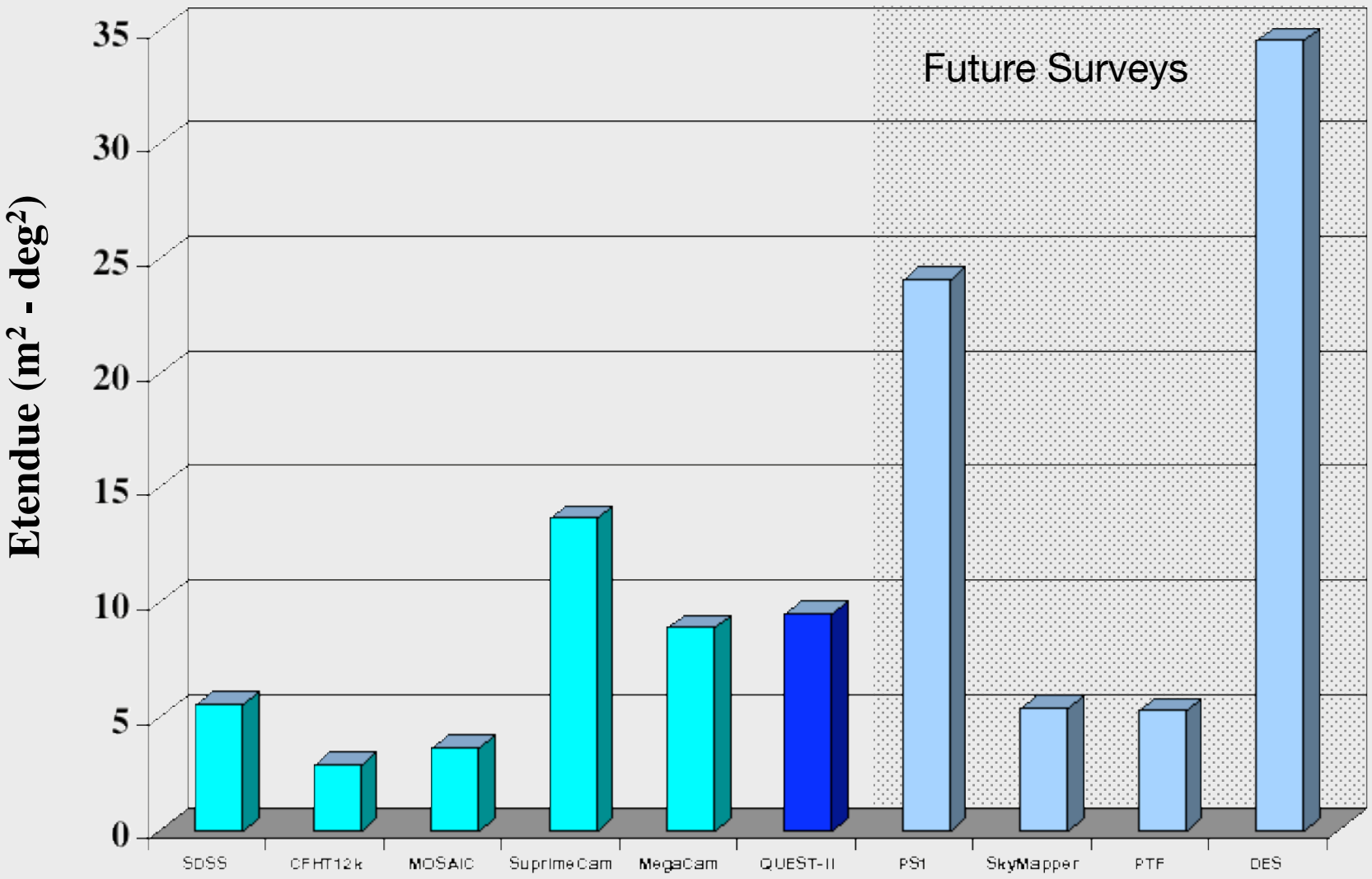
- Fully integrate photometry and spectroscopy
  - *for photometry:*
    - eliminate K-corrections and S-corrections
    - eliminate atmospheric dispersion degeneracies
    - tie flux calibration to calibrated stars
    - tackle dust extinction using more colors
    - self-consistent treatment for all colors
  - *for spectroscopy:*
    - Spectroscopy for more SNe
    - Time series of spectra for each SN
    - properly subtract host galaxy light
    - eliminate effects of slit losses and atmospheric dispersion

Nearby Search More Challenging

SNfactory:
50 Gb per night,
every night

SNLS/Essence:
5 Gb per night,
every 3rd night

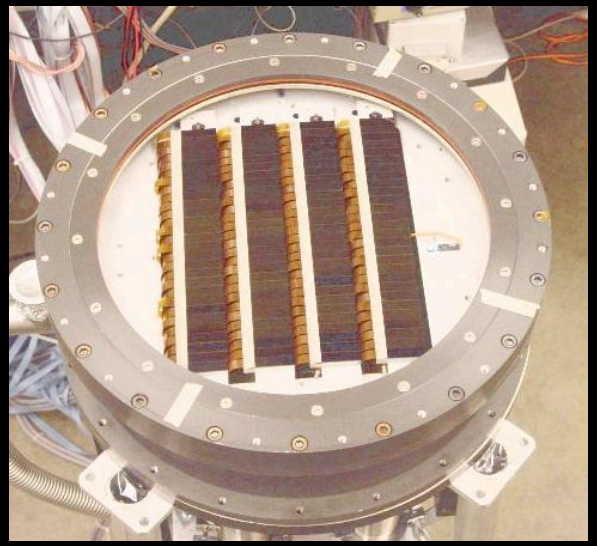


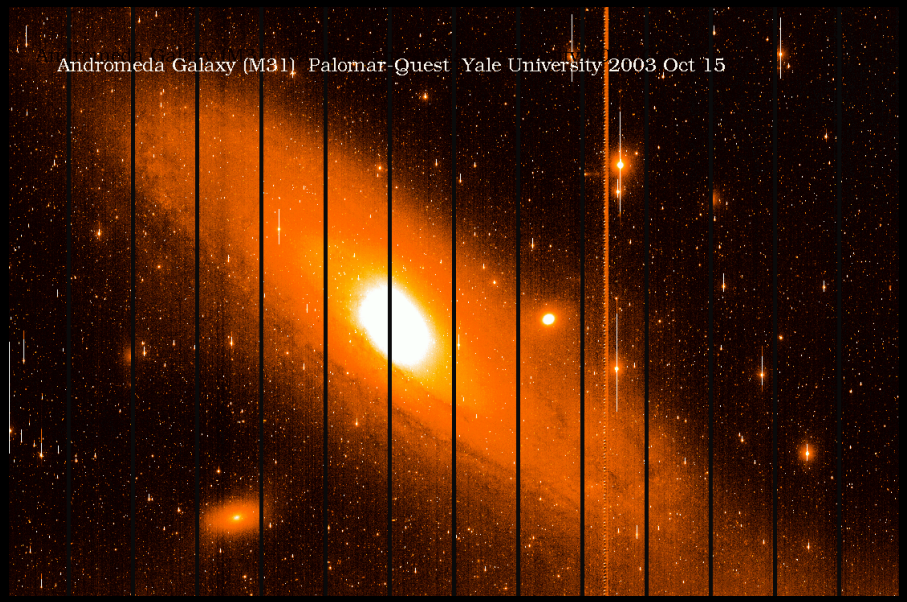

Etendue (m^2 - deg^2)
35
30
25
20
15
10
5
0
Future Surveys
SDSS
CFHT12k
MOSAIC
SuprimeCam
MegaCam
QUEST-II
PS1
SkyMapper
PTF
DES

Palomar-QUEST for SN Search

QUEST II Camera (Yale & Indiana HEP)

- 160 Megapixels
- 112 CCDs
- 2400 x 600 pixels @ 0.87 arcsec/pix
- 9.4 sq. deg
- 40 sec readout time





- 40% of telescope time
- Monitor 1 sr each lunation
- 2π sr over 9 months
- 2 exposures over 1 hr
- 60s or 240s integrations
- RG610 filter

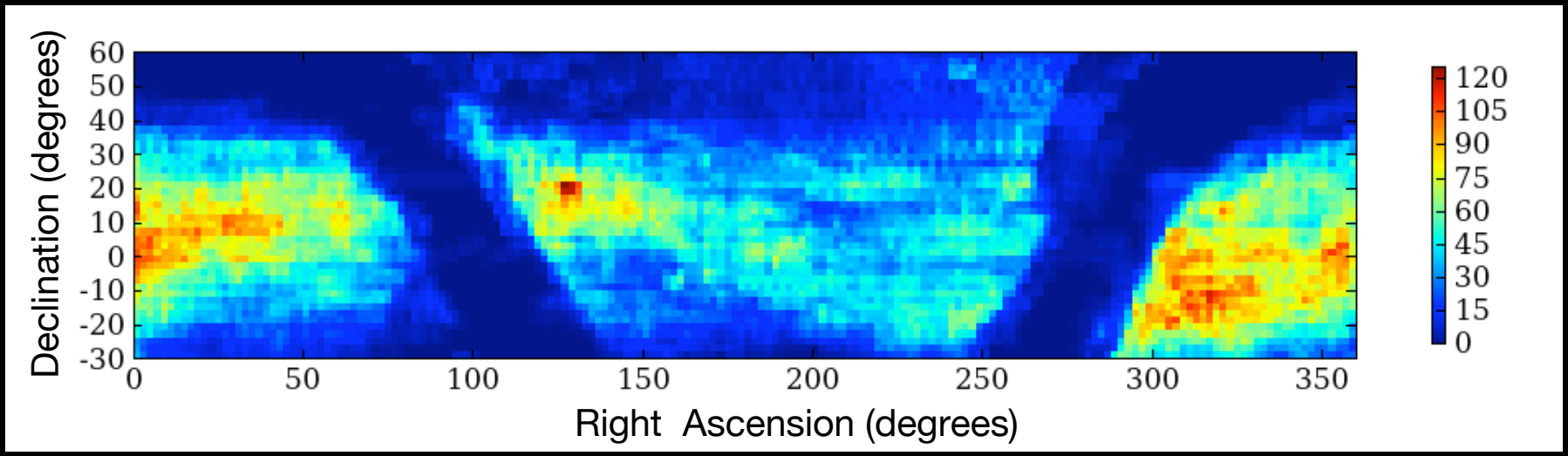
Baltay *et al* 2007

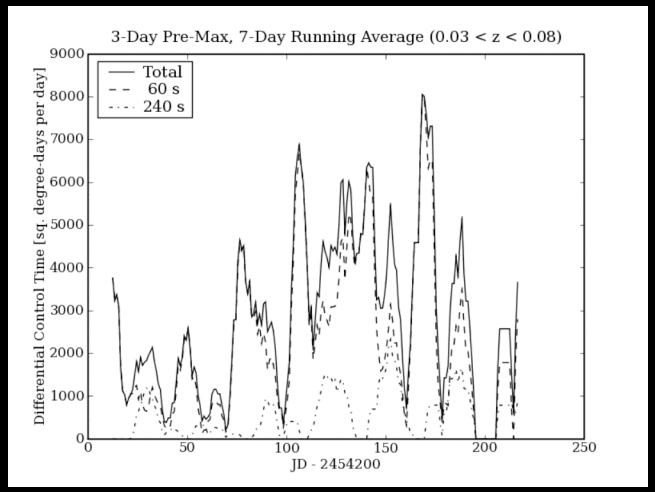
Search Operations

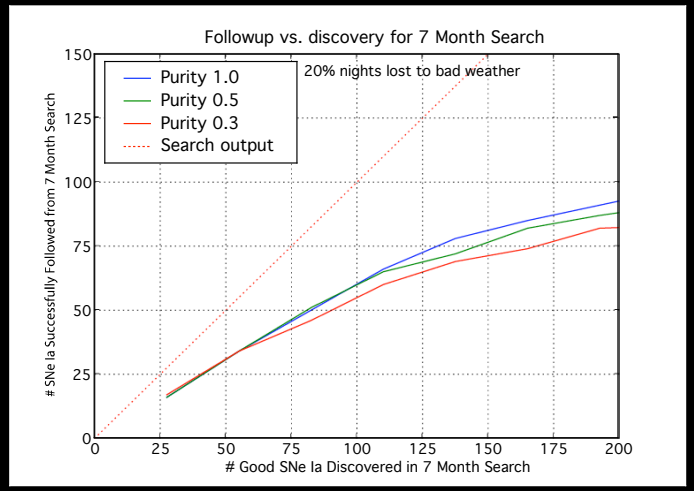
- compose joint TNO - SN schedule
- observation execution at *Palomar*
- data transfer via *HPWREN+ESnet* to *HPSS*
- image processing and registration on *PDSF*
- image subtraction on *PDSF*
- insertion of artificial SNe
- BDT ranking
- `prescan`
- scanning
  - `metascan`
  - `scantng`
- vet candidates
  - `SNwarehouse`
  - `metavet`
  - deep coadd (host galaxy search)
  - historical lightcurve

Running 24/7/220

9 million images so far!

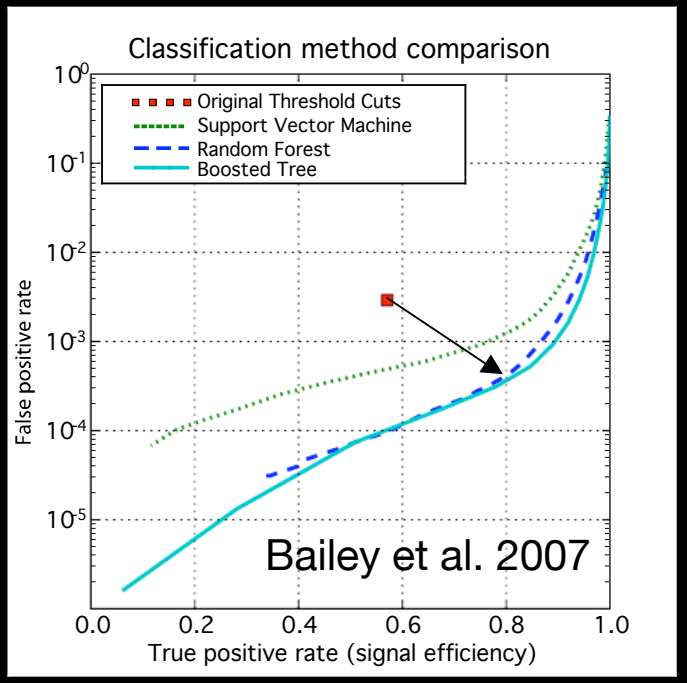


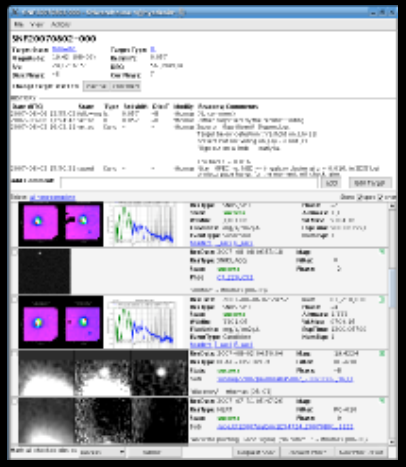




Supernova Search Innovations

- Machine learning techniques:
  - *support vector machine (SVM)*
  - *boosted decision tree (BDT)*
  - *10x suppression of junk*
- 1 day turn-around
- Efficiency measured with fakes
- Flag stagnant asteroid zone
- Warehouse
  - *improved situational awareness*
- Automated data-mining
  - *NASA Extragalactic Database*
  - *Minor Planet Circular*
  - *SDSS*
  - *IAUC SNe*





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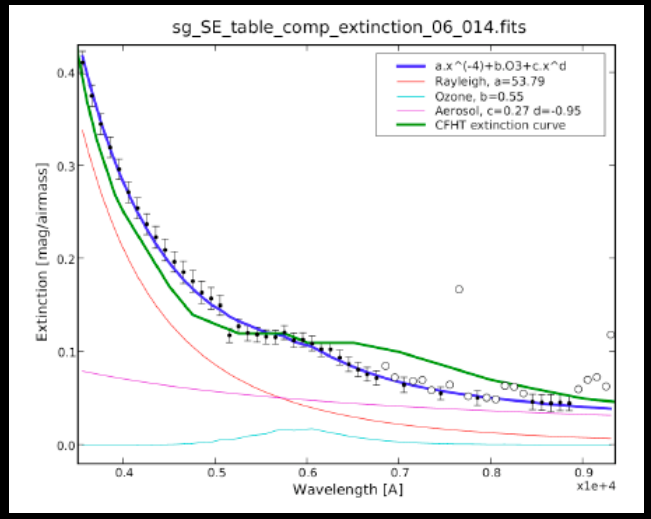
    - self-consistent treatment for all colors
  - *for spectroscopy:*
    - Spectroscopy for more SNe
    - Time series of spectra for each SN
    - properly subtract host galaxy light
    - eliminate effects of slit losses and atmospheric dispersion

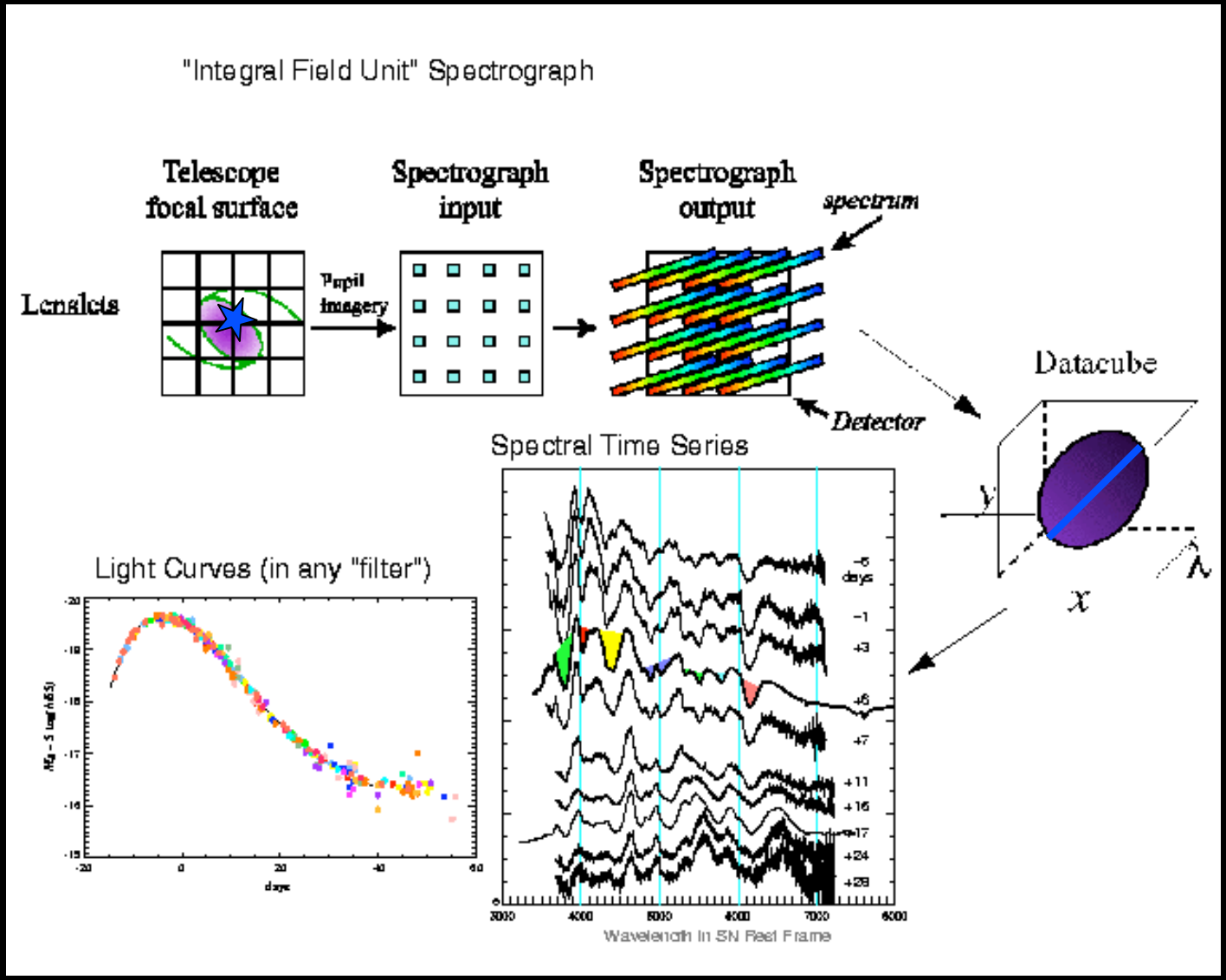
What makes Photometry Hard? The Atmosphere, for One

$$I(x,y,\lambda,t) = [(\mathrm{SN}(\lambda,t)\ \delta(x,y) + \mathrm{Sky}(\lambda,t) + \mathrm{Gal}(x,y,\lambda)) \otimes \mathrm{PSF}(x,y,\lambda,t) \otimes \mathrm{ADR}(\lambda,t)]\, e^{-\sigma_{atm}(\lambda,t)l(t)}$$

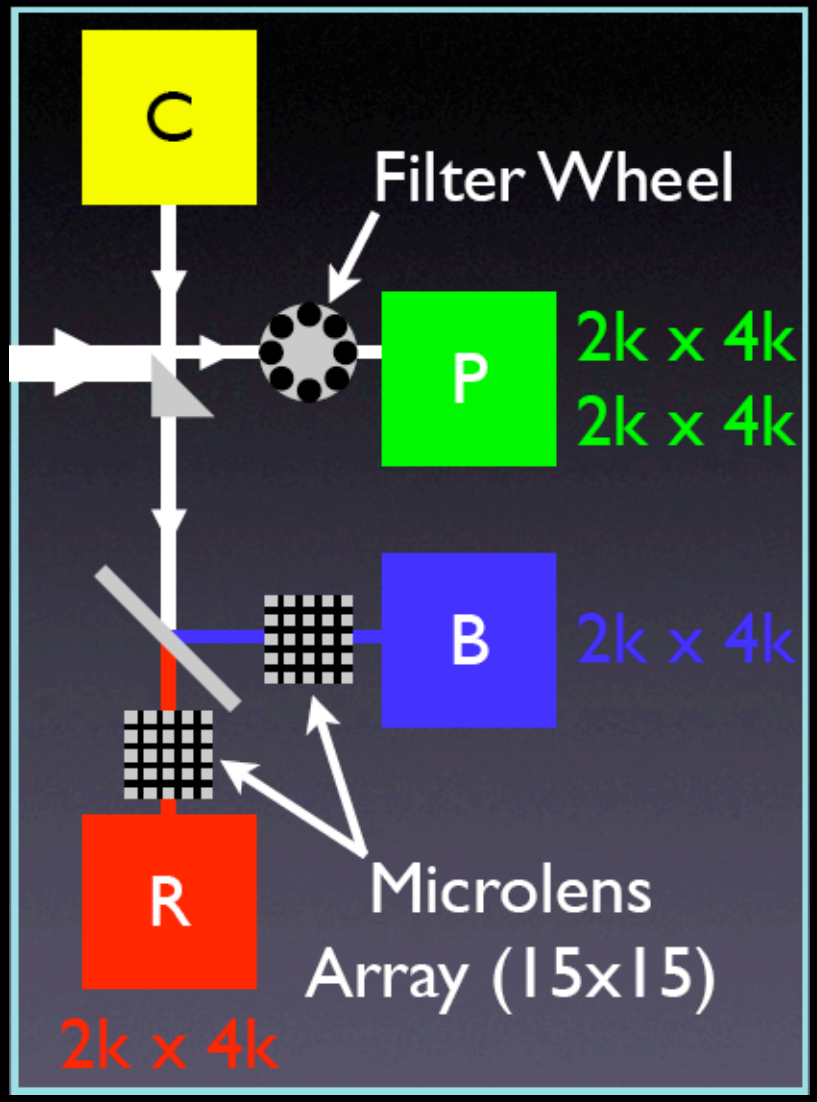


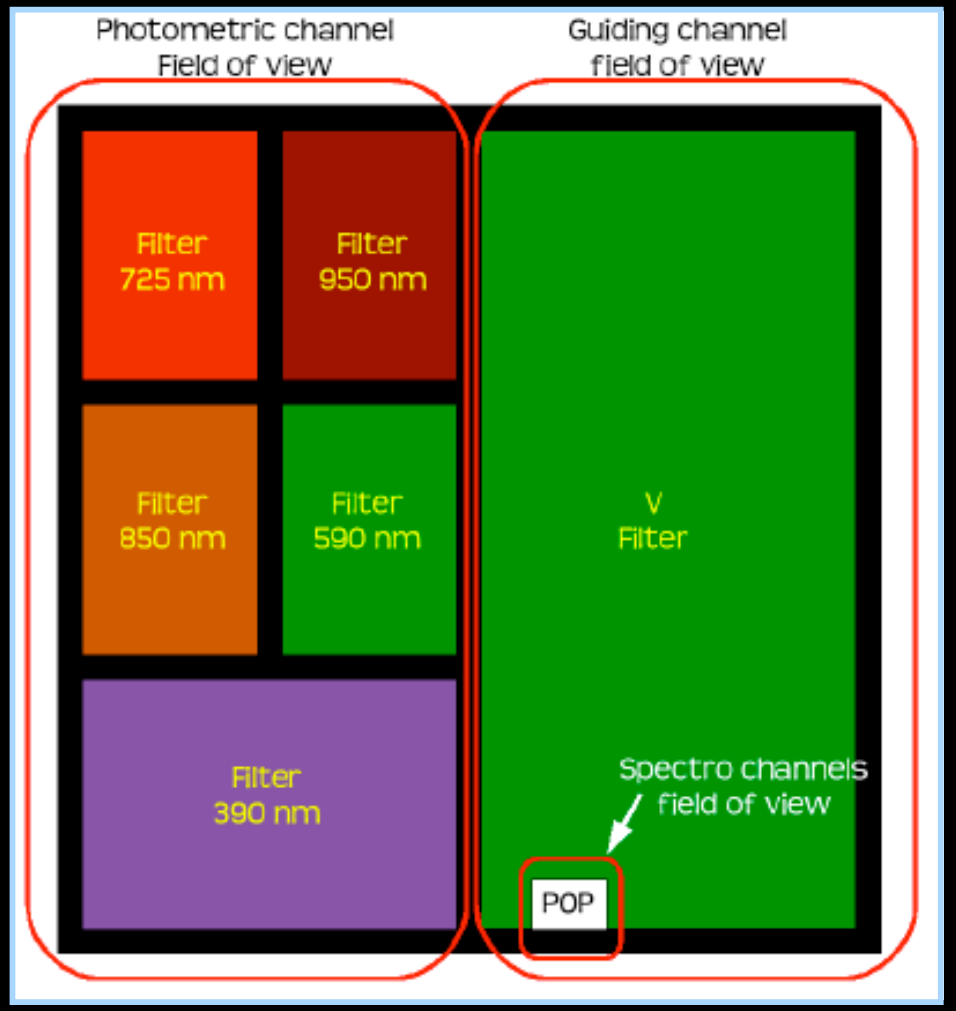
- Scatters/absorbs target light
  - Molecular scattering
  - Aerosol scattering
  - Water vaper absorption
  - O_2 and O_3 (ozone) absorption
  - clouds - H_2O vapor and ice crystals
- Refracts target light
  - Mean refraction depends on position, wavelength and time
  - RMS (seeing) depends on time, wavelength, and position
- Scatters and emits light
  - Emits in atomic and molecular transitions (O, O_2, OH)
  - Scatters sunlight, moonlight, zodiacal and starlight

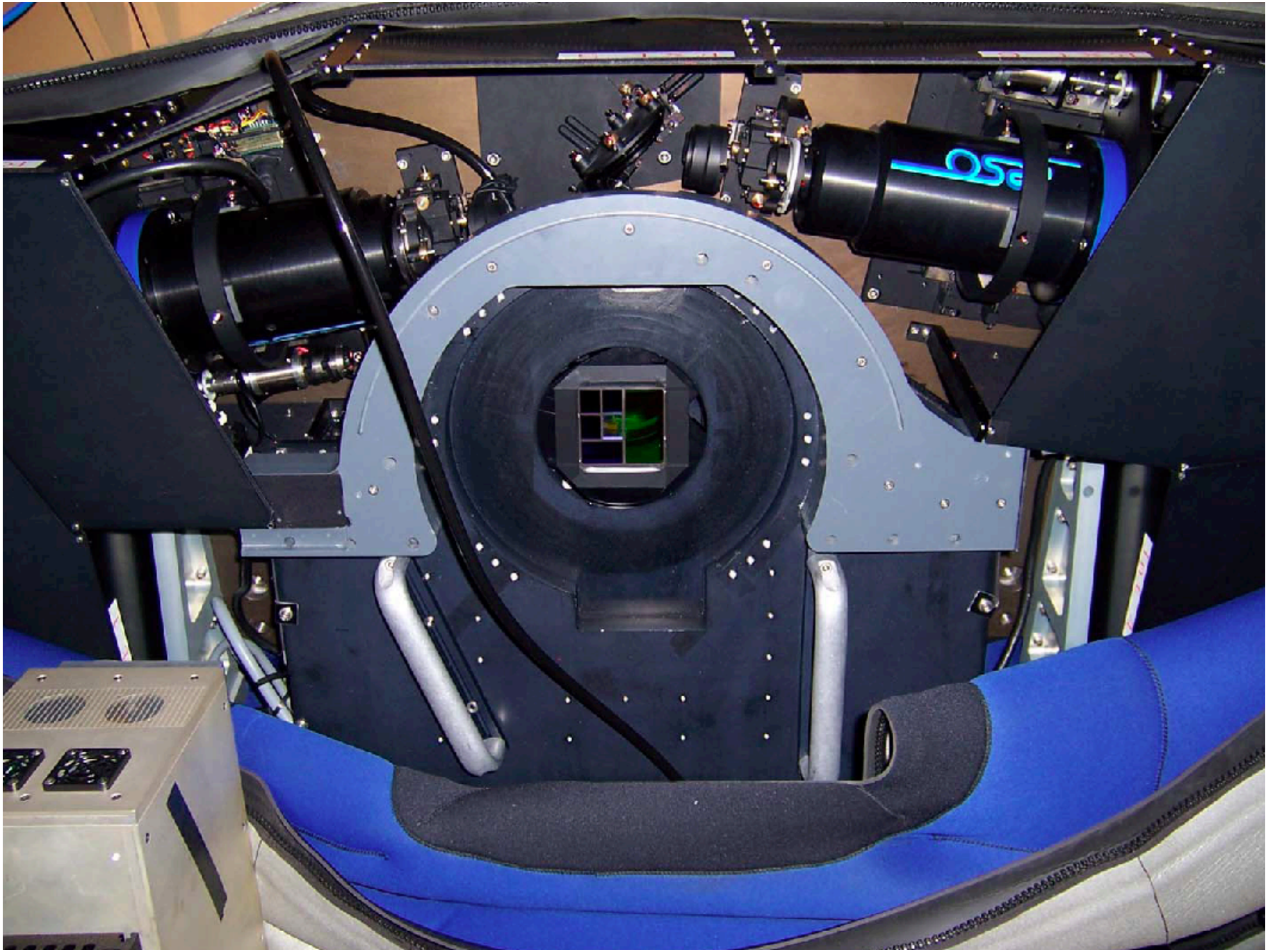
Simultaneous Lightcurves & Spectra!



Schematic SNIFS Layout

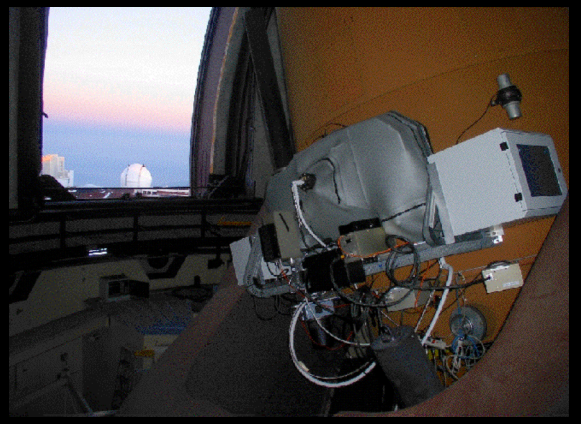




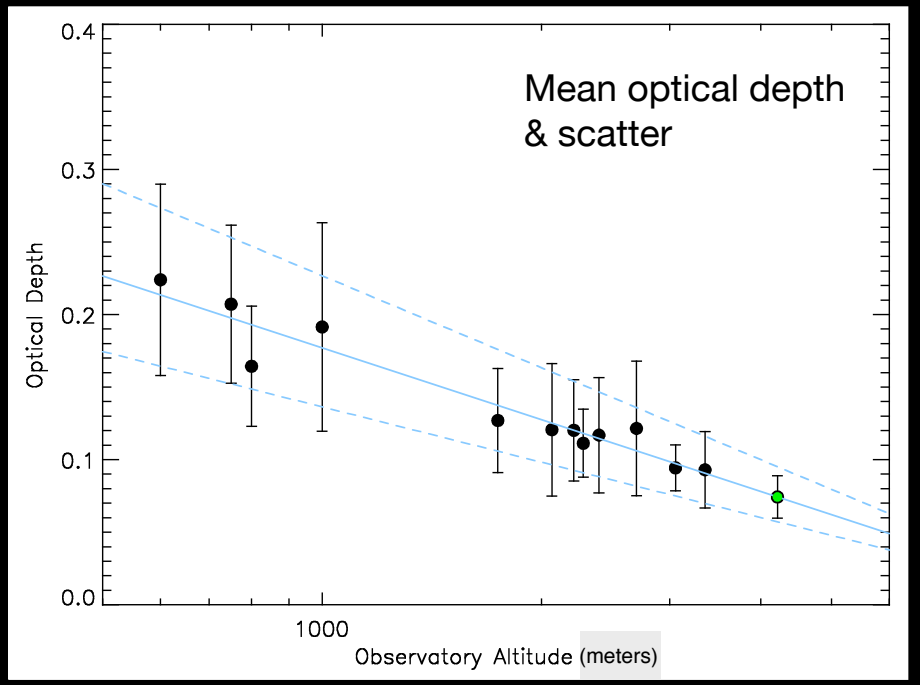


UH 2.2-m Telescope & Site

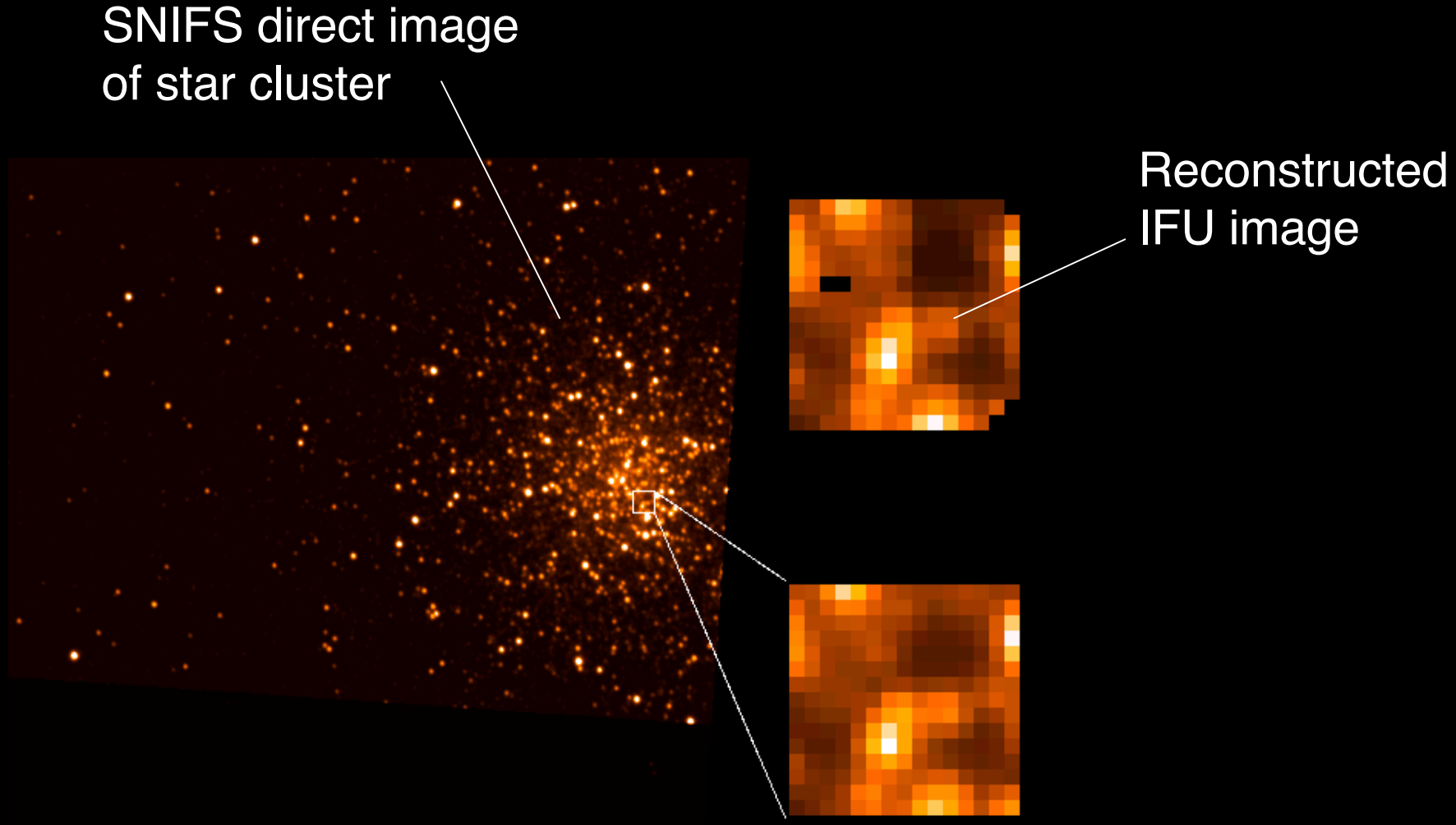
- Mauna Kea Site Properties
  - known for excellent image quality
  - atmospheric extinction the lowest
  - atmospheric extinction the most stable
  - slightly less differential refraction
  - moonlit sky is darker



- UH Telescope properties
  - excellent stray-light baffling
  - easy to swap in SNIFS
  - *limited thermal control*
  - *telescope can get stuck*
  - *dome can get stuck*



SNIFS IFU Example

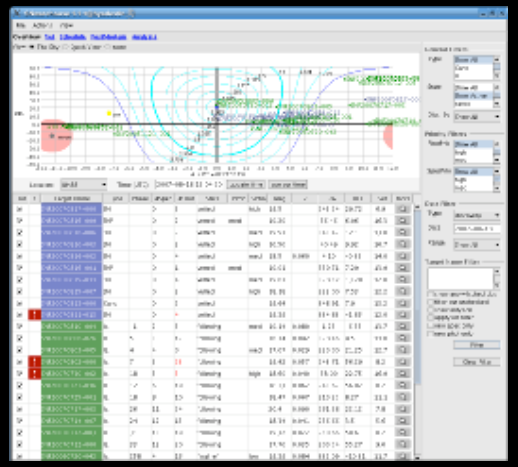


SNIFS Data Acquisition

- Scripted afternoon and morning internal calibration
- Auto-focusing of spectrograph
- Auto-orienting of telescope on inclinometers, then stars
- Auto-calculation and execution of twilight flats
- Auto-focusing of telescope w/ temperature adjustment of range
- Automatic field acquisition and guide star selection
- Automatic standard star selection
  - *latin hypercube on airmass and spectral type*
- Candidate screening
  - `check_match` *screening*
  - *photometric screening*
- Immediate preliminary data reduction and quality assurance
- DAQ software extended to include backgrounding
- Automatic unsticking of the telescope (darn Mobile Flying Horse Telescope Oil #3!)

SNIFS Data Acquisition Helpers

- `Scheduler`
  - automated and/or custom adjustments
  - rounds up digital finder charts
  - ships schedule and charts from LBL to summit
- `Datataking`
  - presents schedule
  - target sky location
  - results of quick data reduction
  - homogenous evaluation of outcomes
- `AIC` - Automated Instrument Control
  - executes high-level scripted sequences
  - interlock against dome lights and Sun
- `CrowBot9000`
  - lives in cyberspace (`GAIM`)
  - alerts user to `AIC` events
  - alerts user to twilight/need to refocus/proximity to Moon
  - can be interogated about Sun, Moon, and standard stars
  - can issue alert to on-call instrument specialist
  - psychiatrist for bored or troubled shifter



Raw and Derived Data Products

Product	Science	Photo-metricity	Flux Calibration	PSF
B & R SN spectra	✓			✓
B & R Std spectra		✓	✓	✓
Muiltfilter Image		✓	✓	✓
Acquisition Image	✓	✓		✓
Guide star video		✓		✓
Set-up Star image				✓
Focus series				✓
CFHT Skyprobe		✓		

Not without a few Calamities!

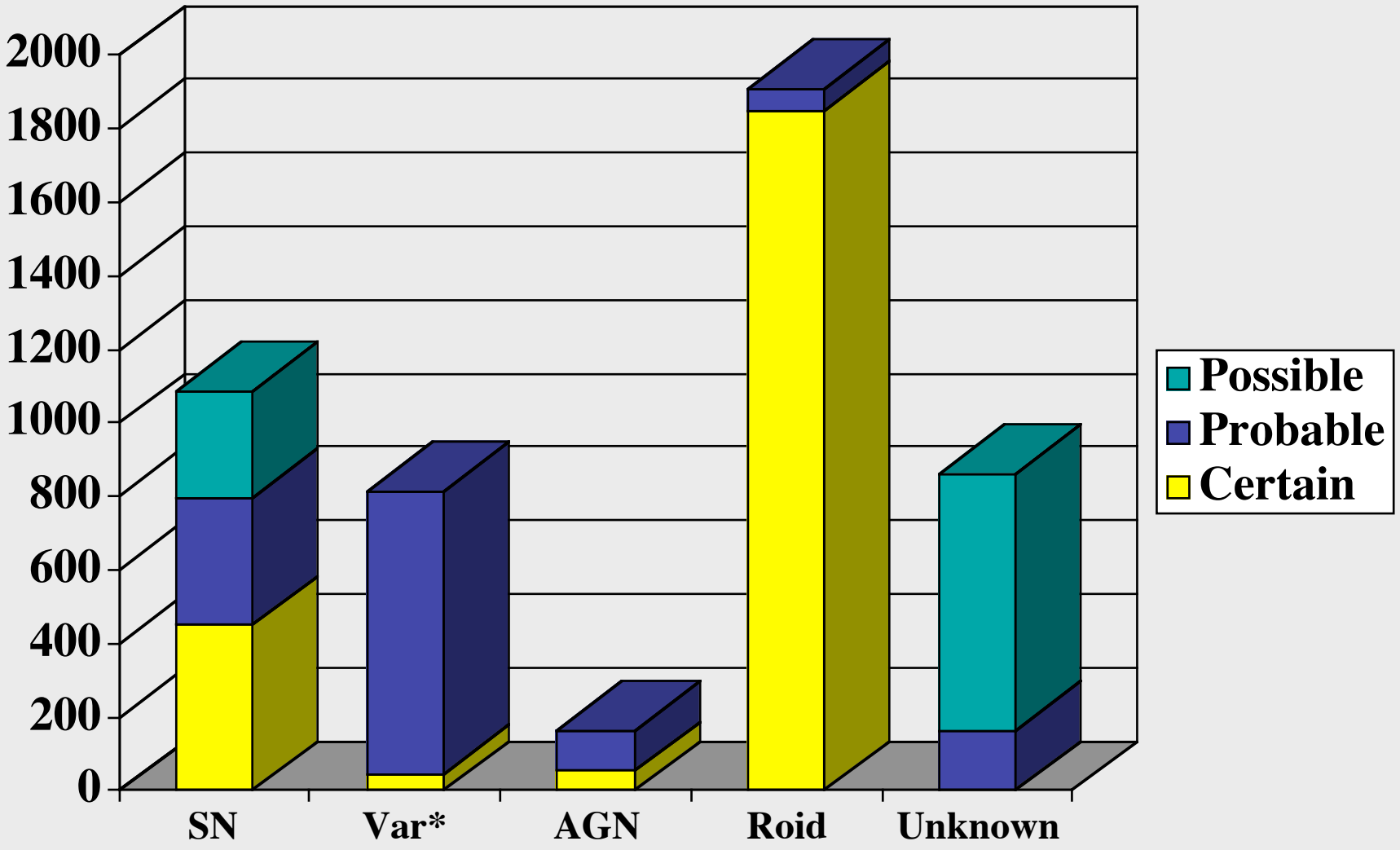
Fire closes
Palomar Observatory

Mag 6.7 earthquake hits Mauna Kea

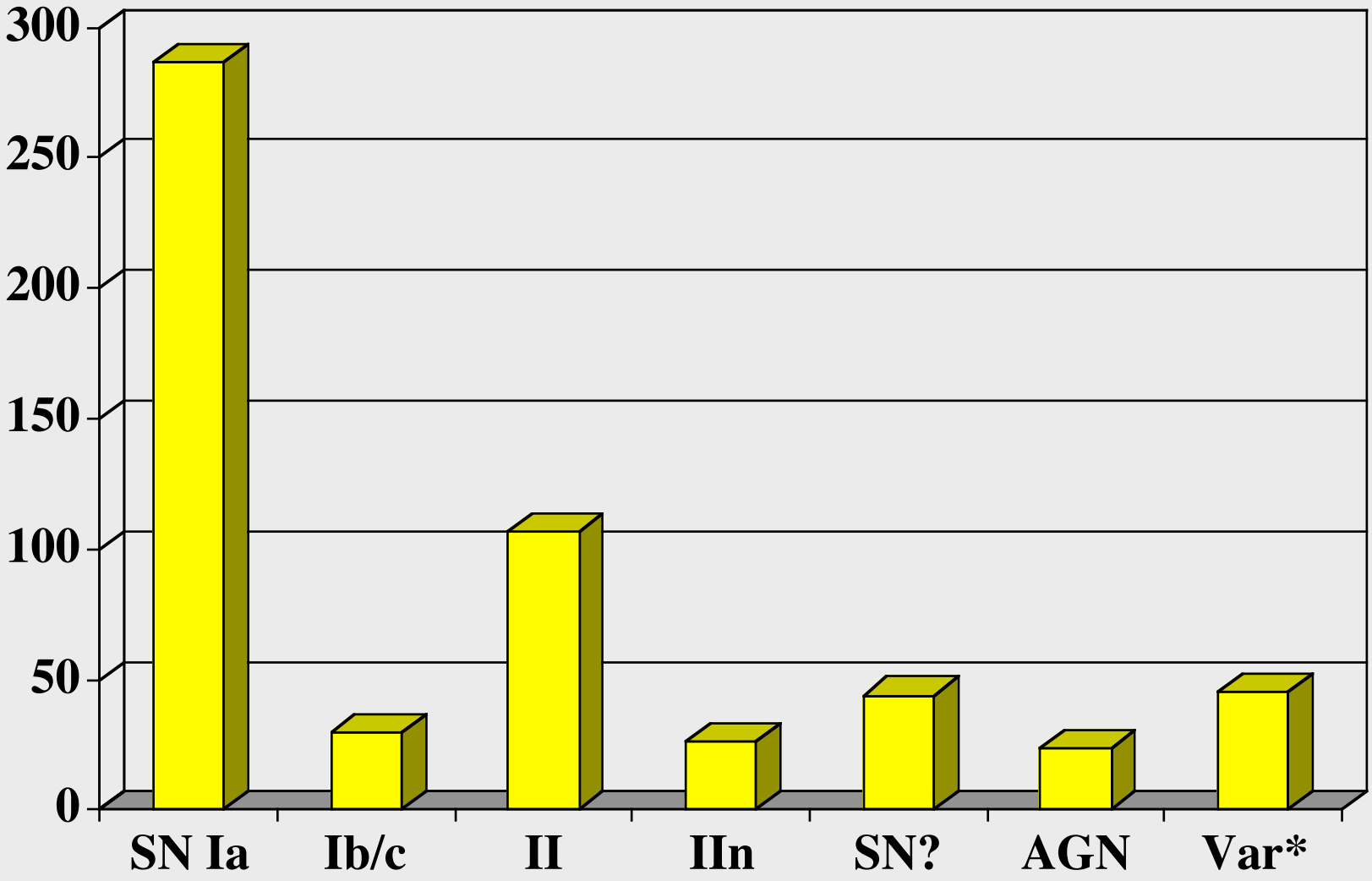
- Altitude sickness afflicts three during commissioning
- LIPS crushes SNIFS cooling lines
- QUEST camera dewar springs leak

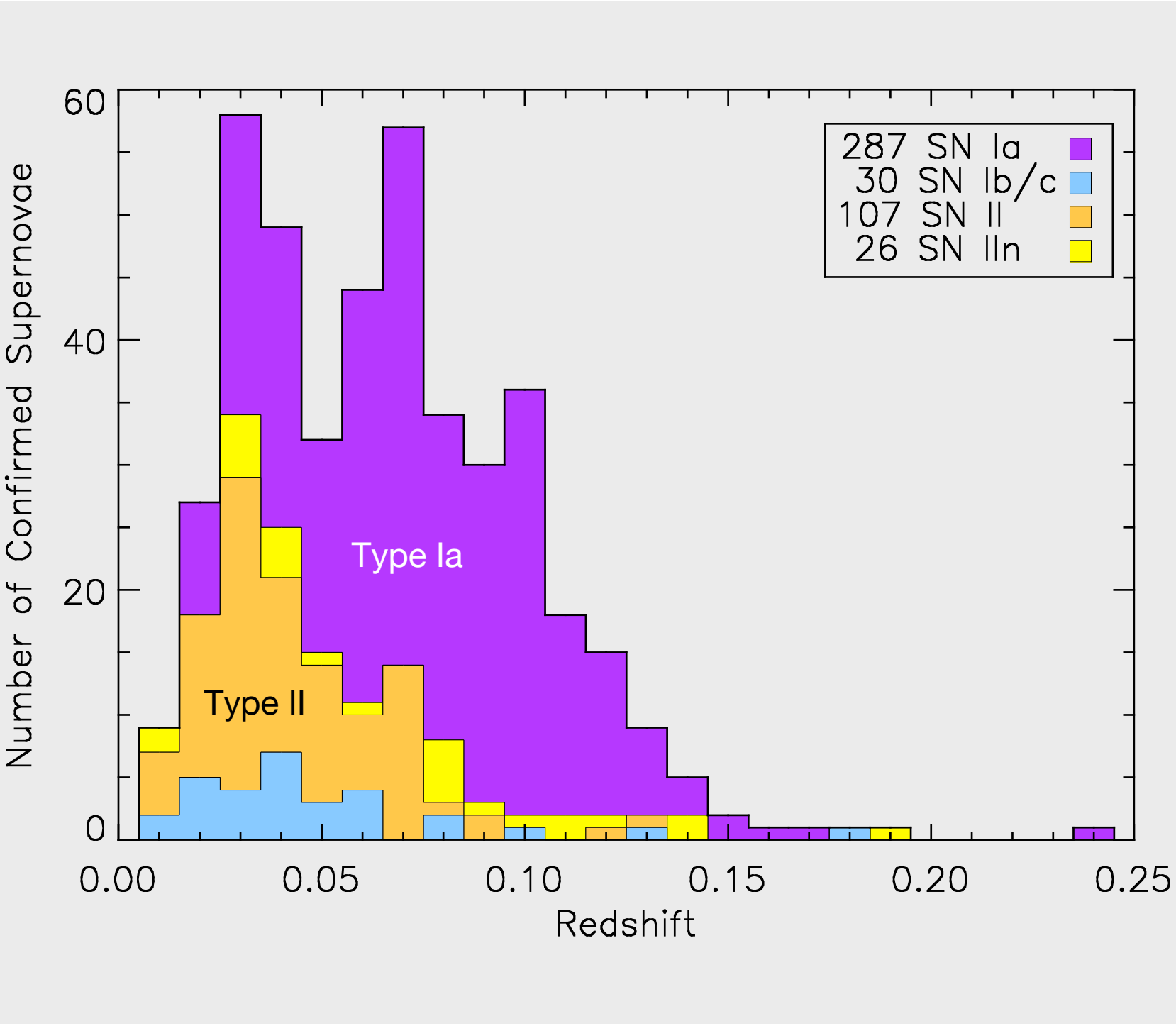
Fire sweeps antenna site at North Peak

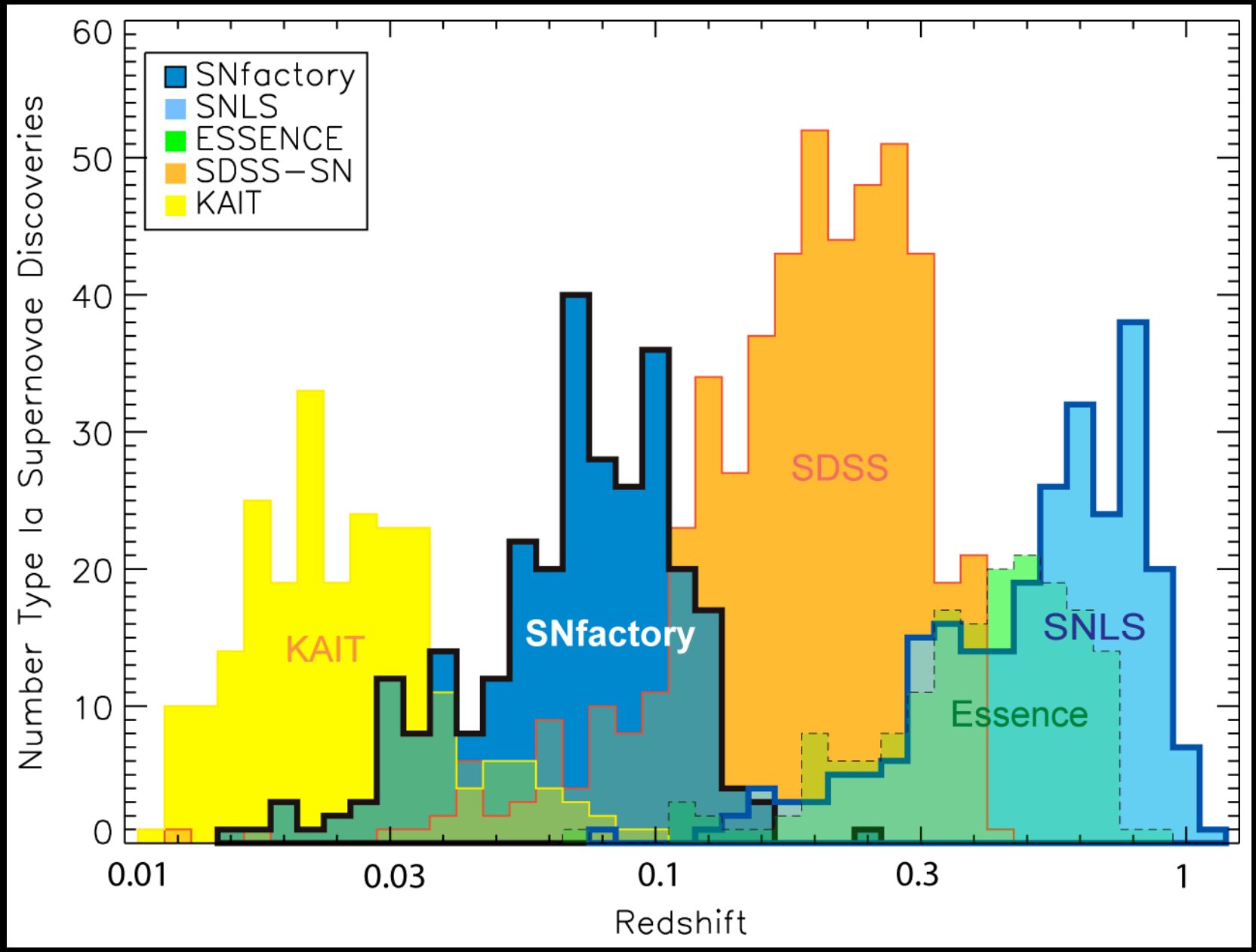
Search Sample Composition



Spectroscopic Sample Composition




287 SN Ia
30 SN Ib/c
107 SN II
26 SN IIn
Type Ia
Type II
Number of Confirmed Supernovae
Redshift
0
20
40
60
0.00
0.05
0.10
0.15
0.20
0.25


SNfactory
SNLS
ESSENCE
SDSS−SN
KAIT
Number Type Ia Supernovae Discoveries
60
50
40
30
20
10
0
0.01
0.03
0.1
0.3
1
Redshift
KAIT
SNfactory
SDSS
SNLS
Essence

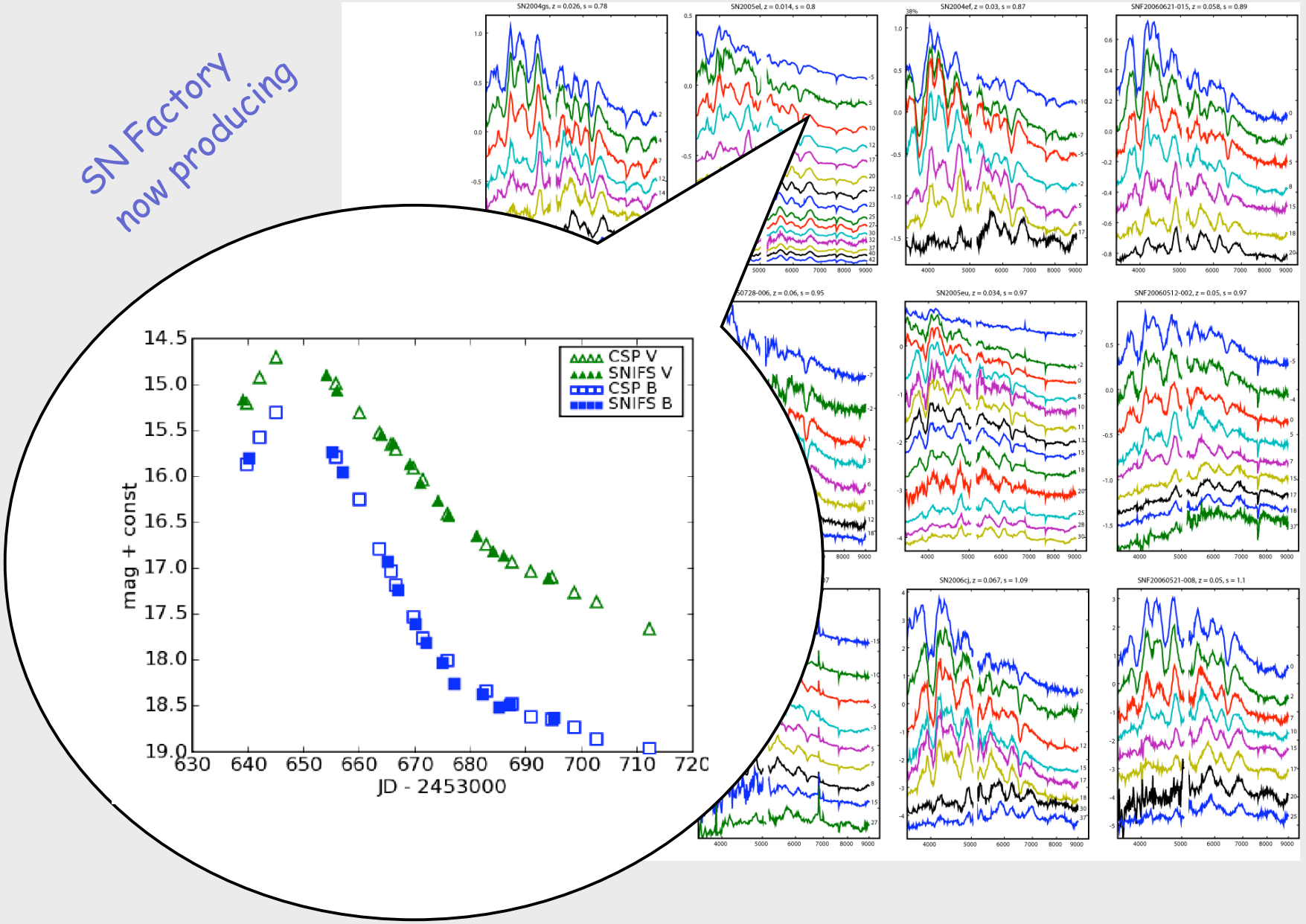
Preliminary Type Ia Rates

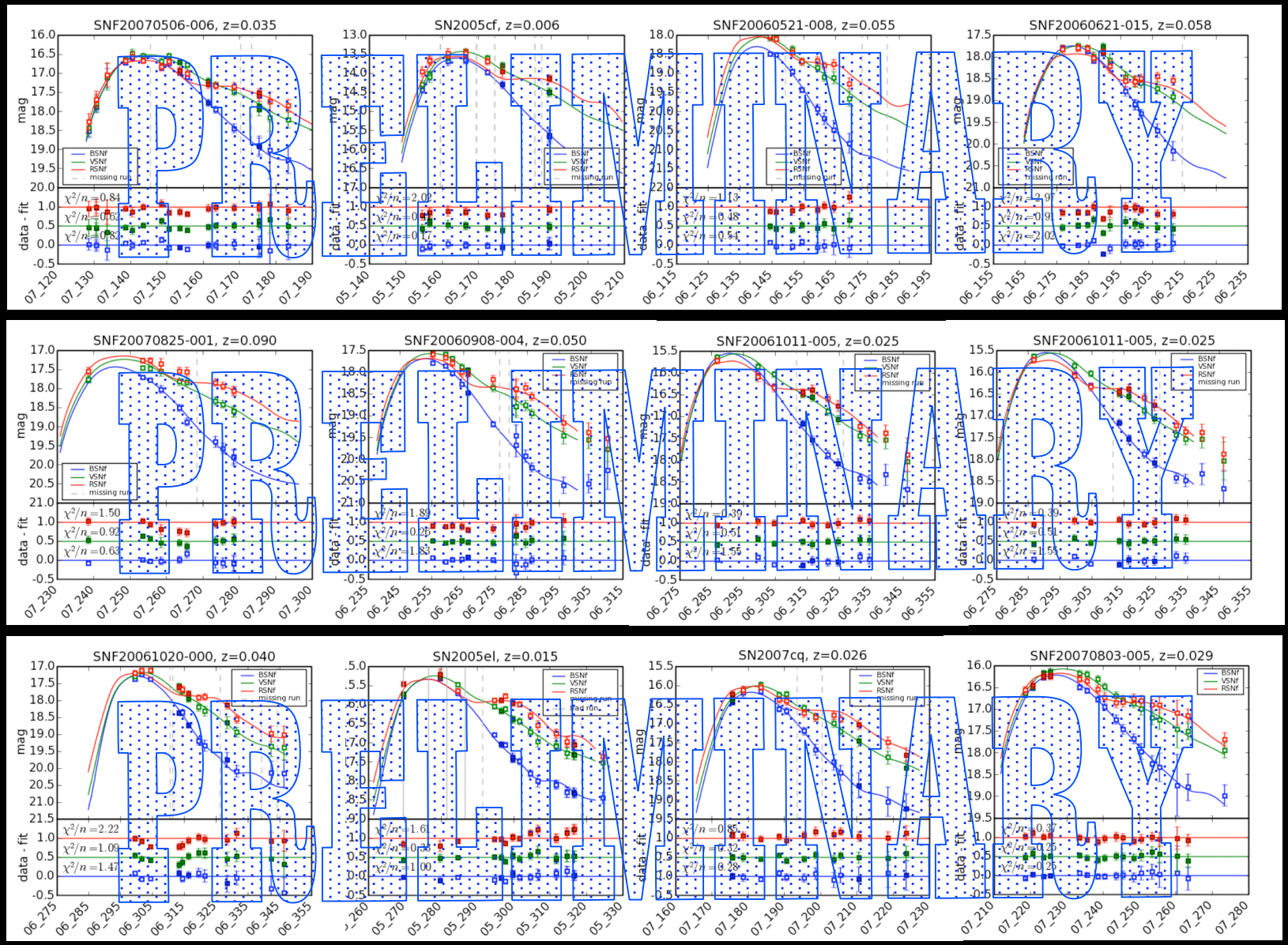
Number of pre-max SNe Ia
per 1000 sq. deg. per 6 month
$0.03 < z < 0.08$

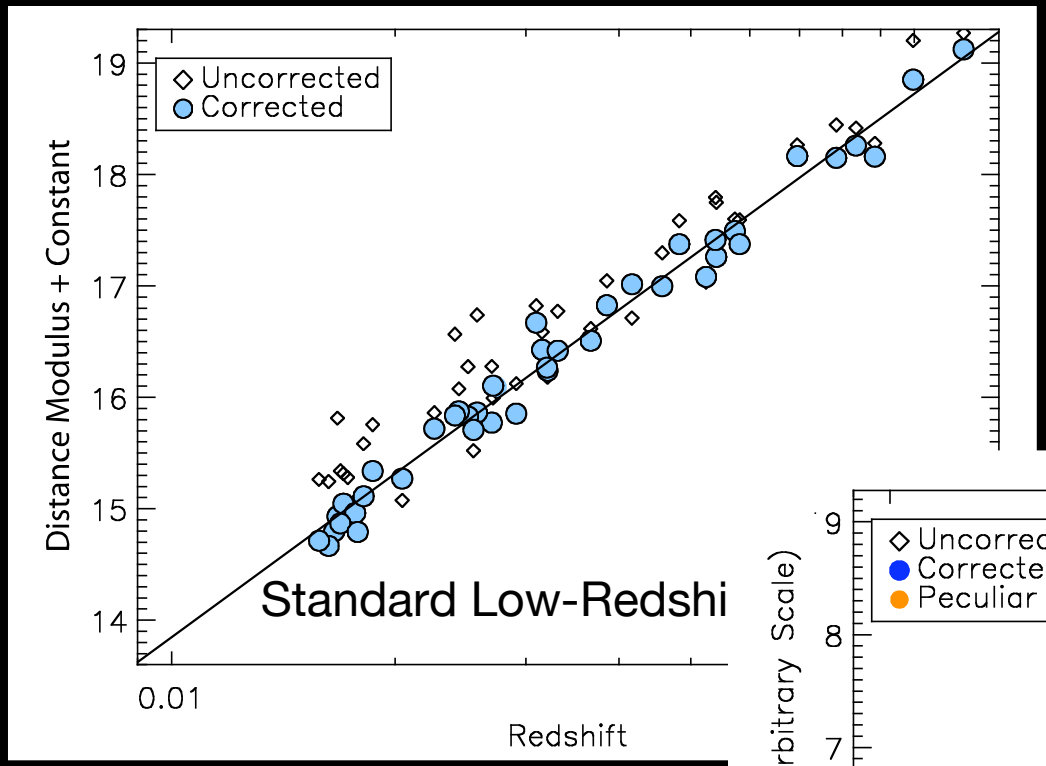
SNfactory 6 month total after correcting for detection inefficiency	Monte Carlo simulated 6 month total using SDSS-SN rates	Monte Carlo simulated 6 months total using weighted mean low-*z* rates
21.7 +/– 3.8	**29.2 +/– 8.4**	**24.1 +/– 2.5**

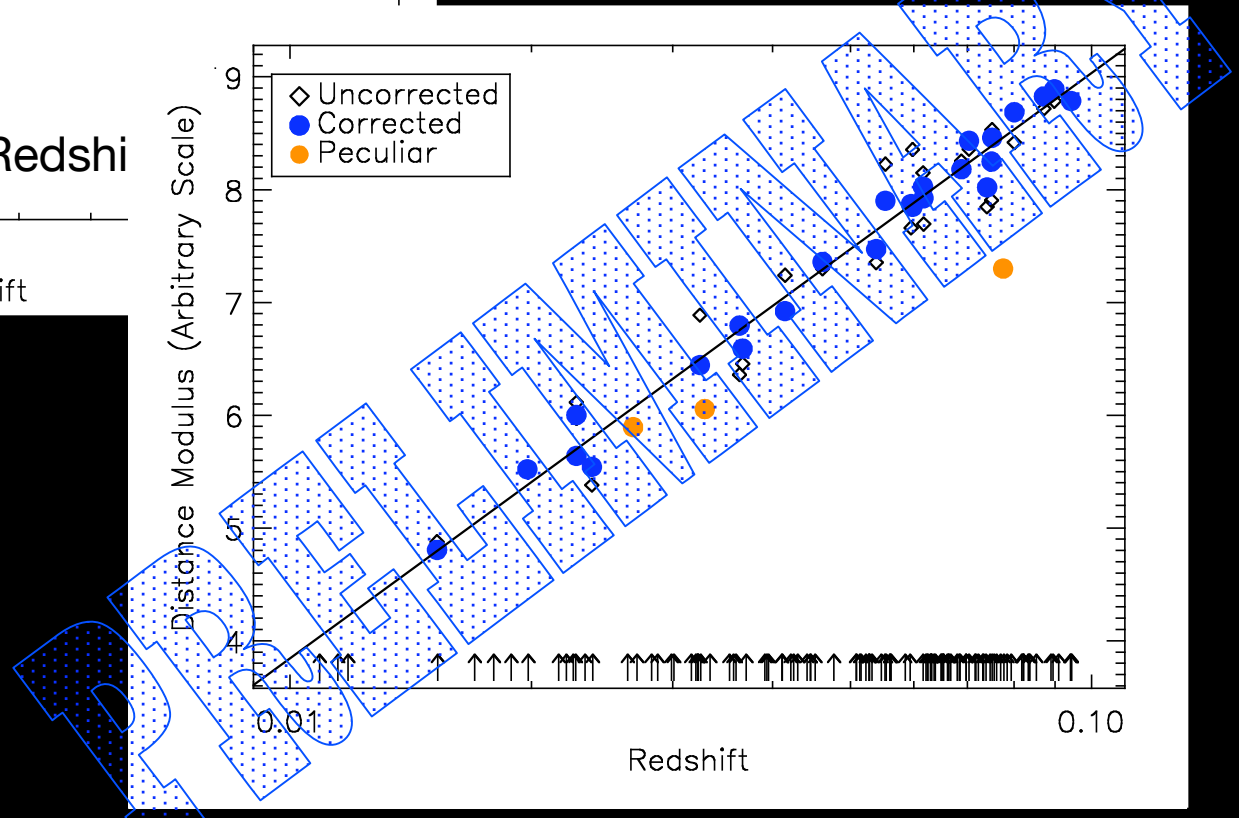
Realized: Library of Spectral Time Series

SN Factory
now producing

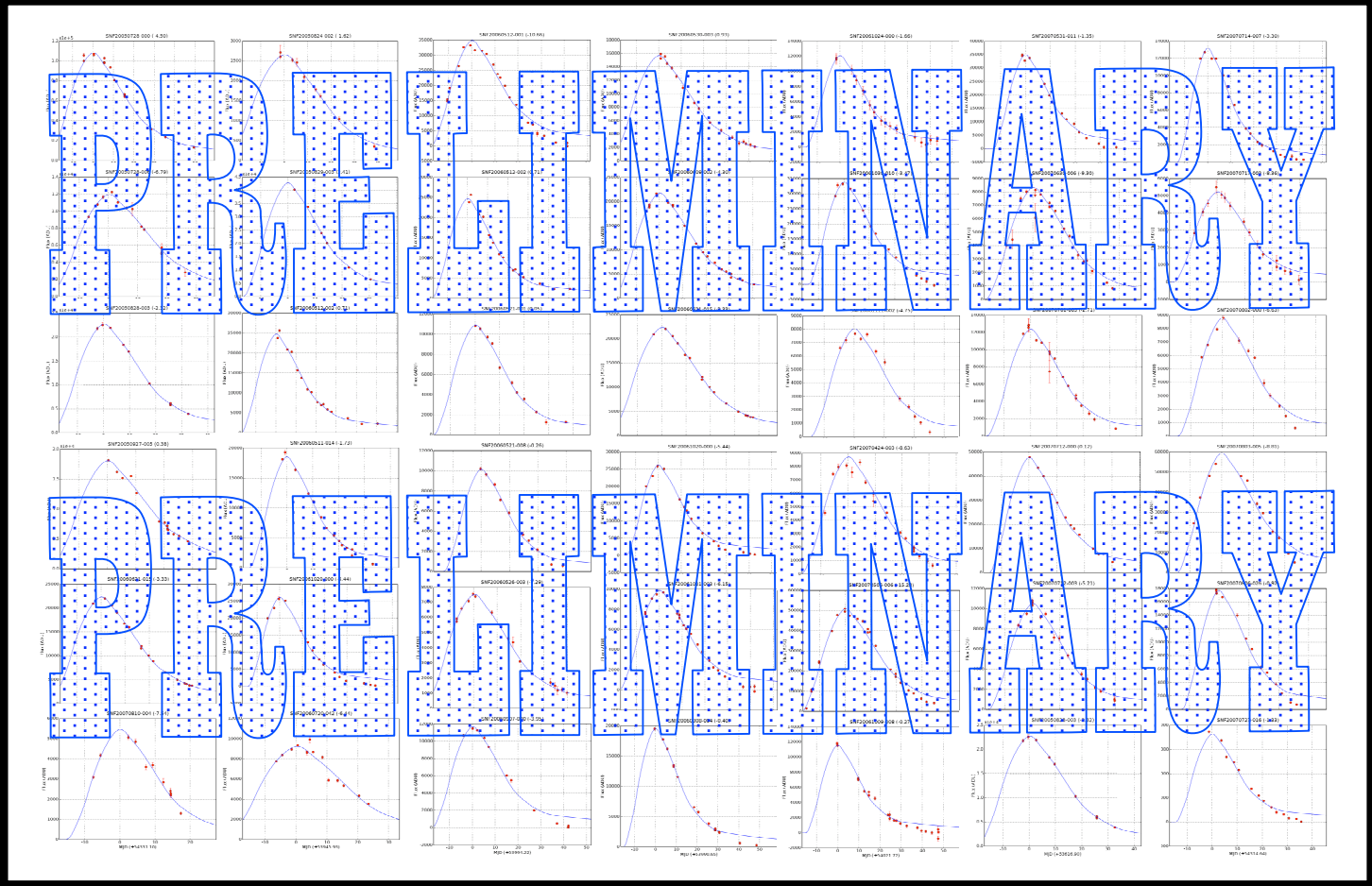



SNF20070506-006, z=0.035
SN2005cf, z=0.006
SNF20060521-008, z=0.055
SNF20060621-015, z=0.058
SNF20070825-001, z=0.090
SNF20060908-004, z=0.050
SNF20061011-005, z=0.025
SNF20061011-005, z=0.025
SNF20061020-000, z=0.040
SN2005el, z=0.015
SN2007cq, z=0.026
SNF20070803-005, z=0.029
BSNf
VSNf
RSNf
missing run
mag
data - fit





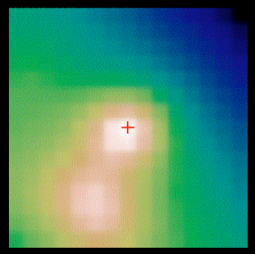
Can X-Check with Classical Photometry



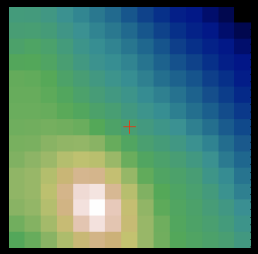
R. Pereira thesis - using V-band acquisition images

Full Multi-Epoch Foreword Modeling

N Datacubes w/ SN

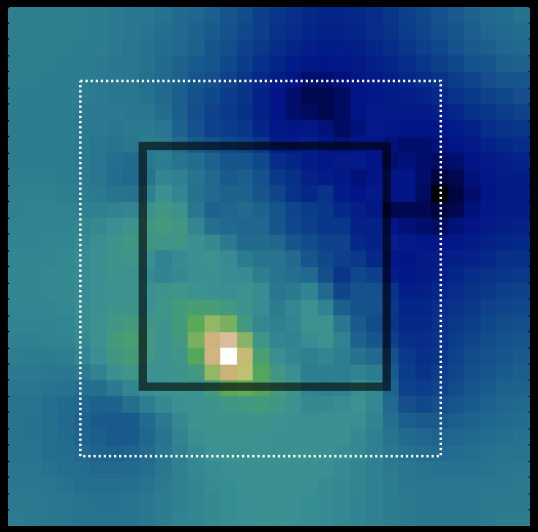


Datacube w/o SN



- Regularize PSF_i in wavelength
- Spatially regularize galaxy
- Spatially regularize PSF_i

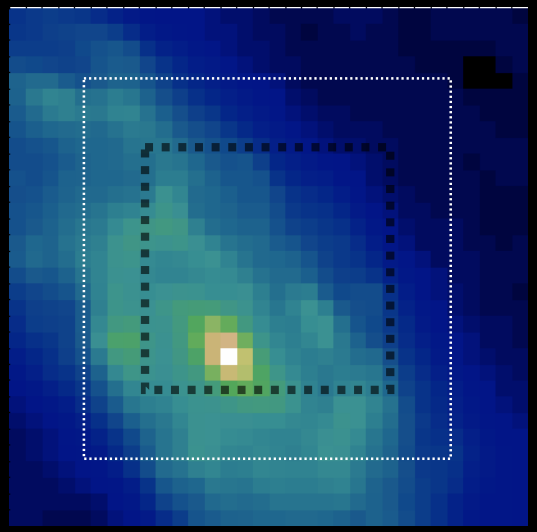
Galaxy Model

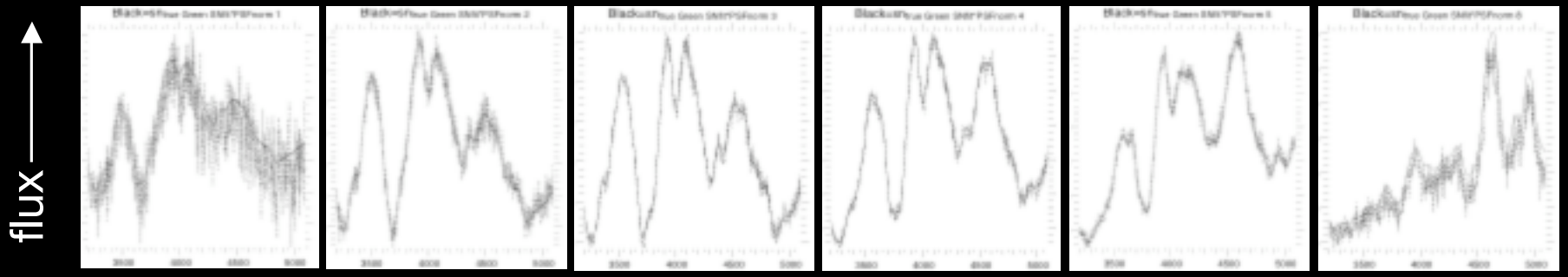


← MLA support →

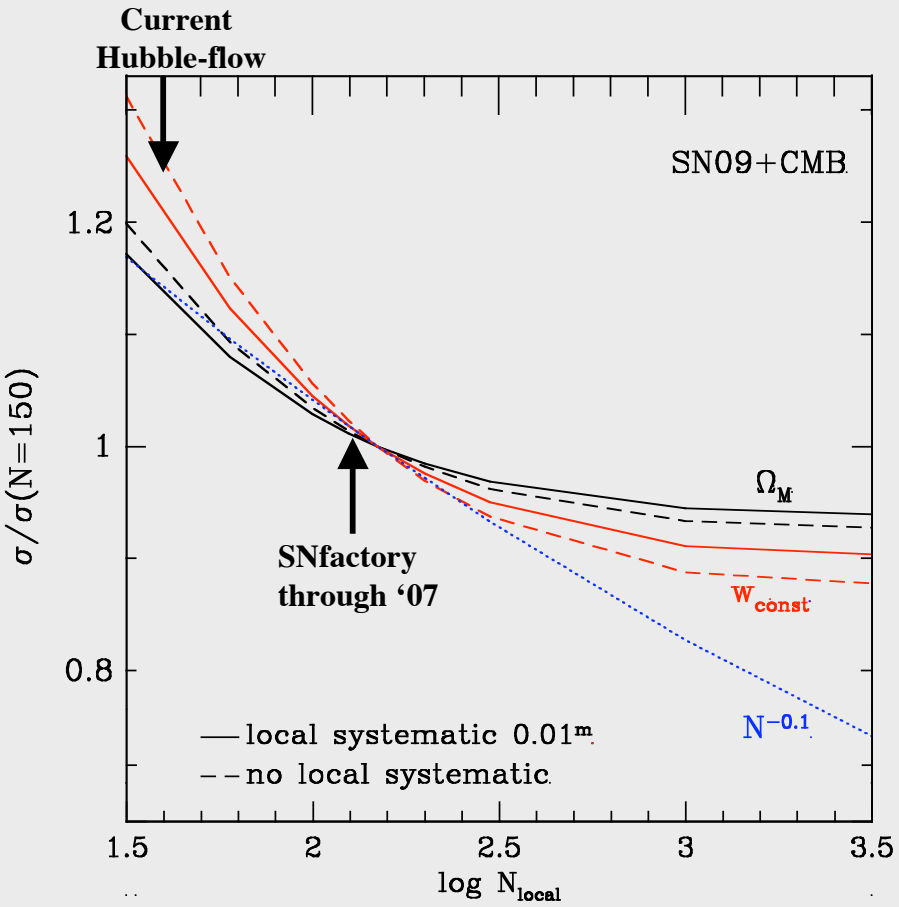
← MLA support+FWHM →

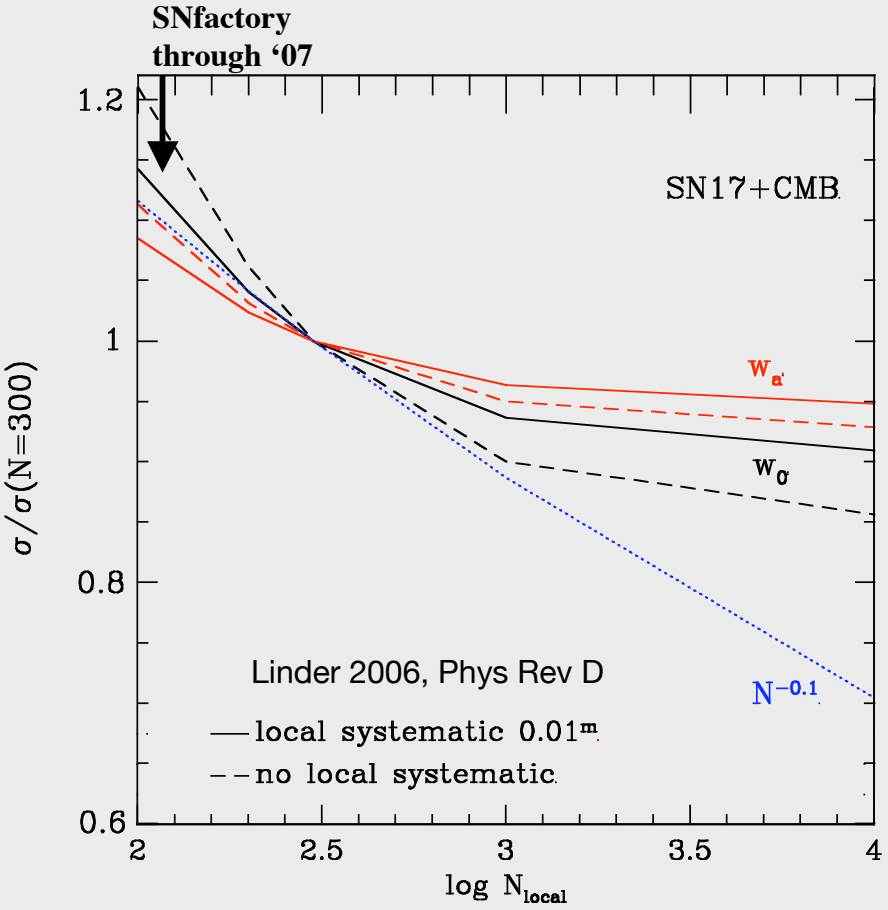
Real Galaxy Image



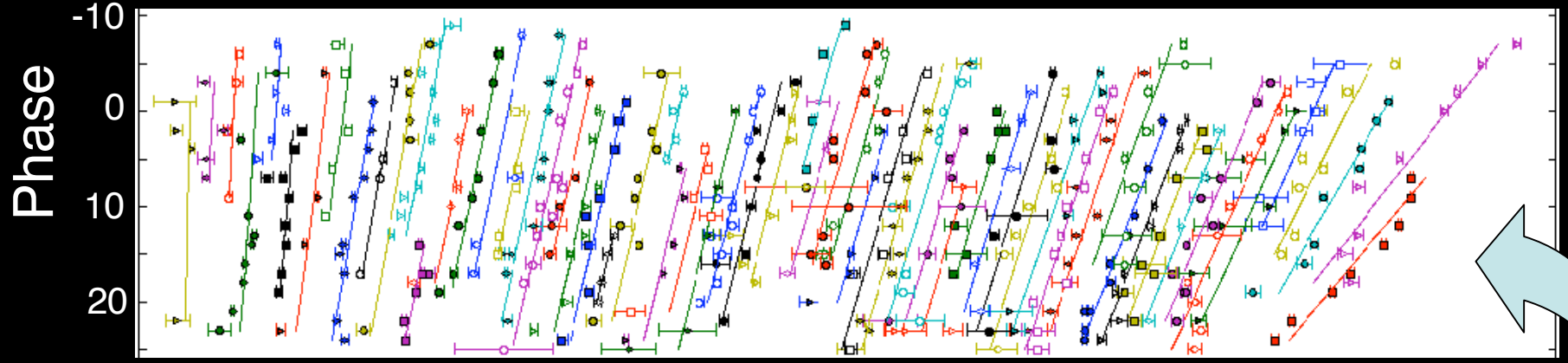


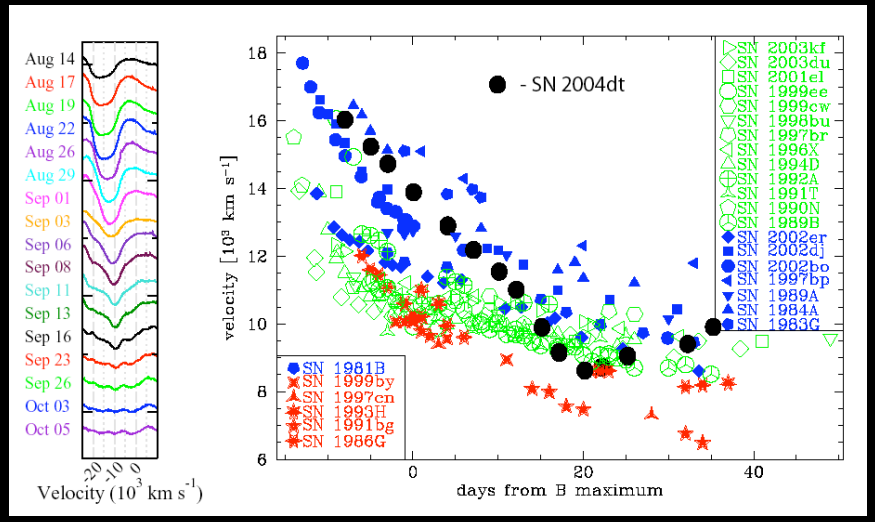
Projected Statistical Gains

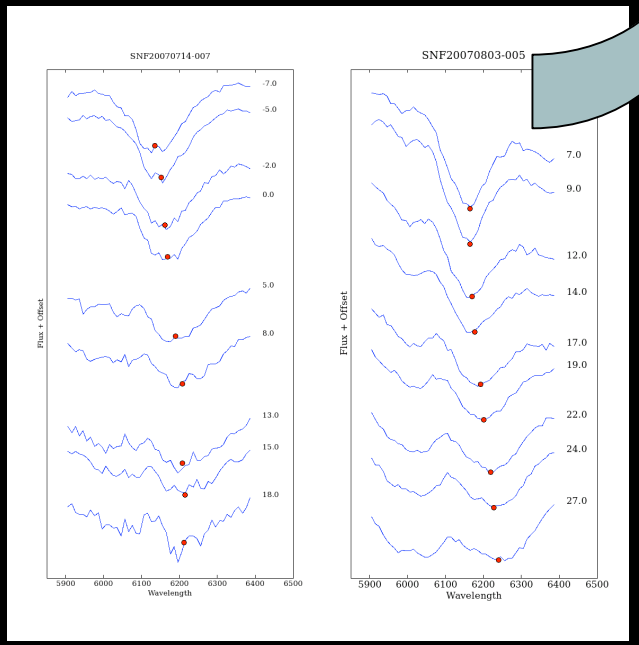




V_{Si} (offset and ranked by slope)



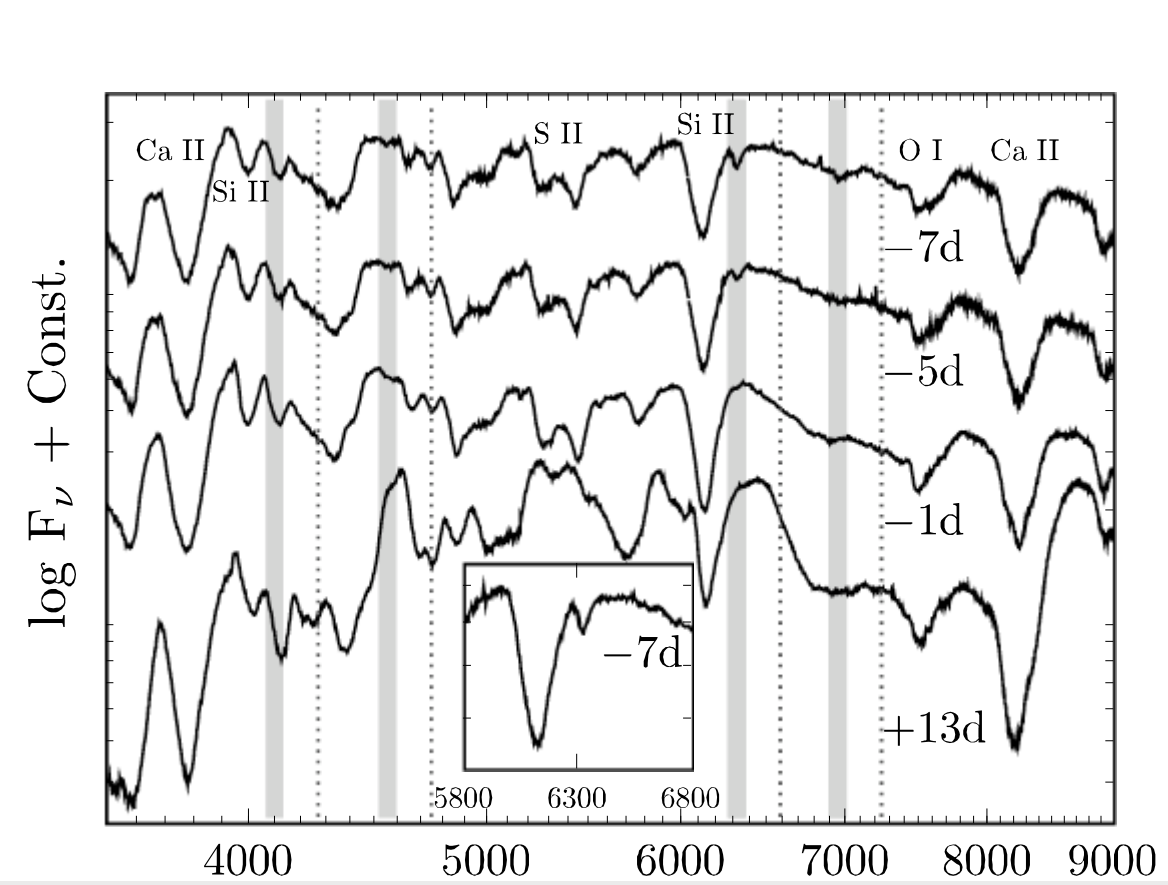




Most of ours *are* in the Hubble flow!

Childress *et al* 2008

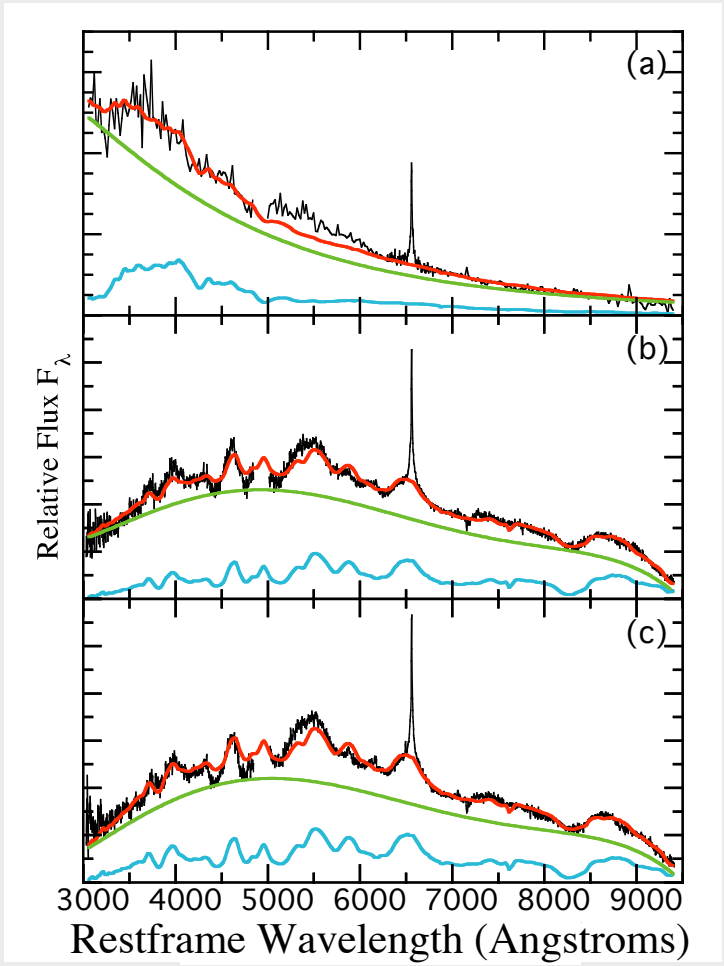
Unburned Material Constrains Explosion Mechanism

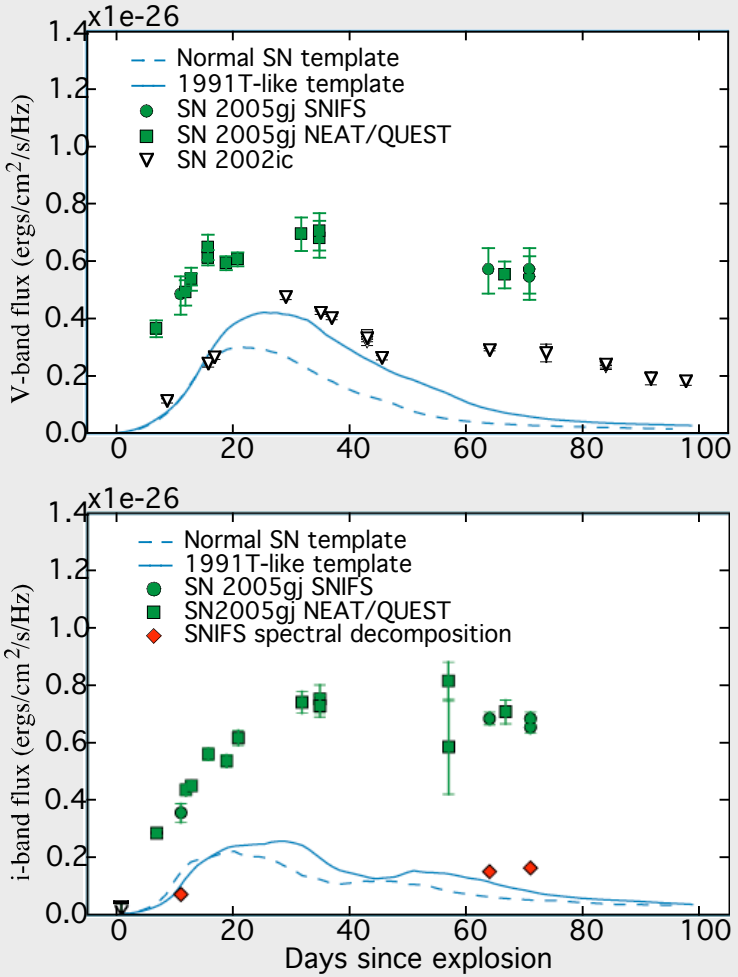


SNfactory spectrum of SN2006D shows first clear evidence for unburned material - Carbon at photospheric velocity.

Thomas et al. 2007

Discovery Ties SN Ia to Normal Stars

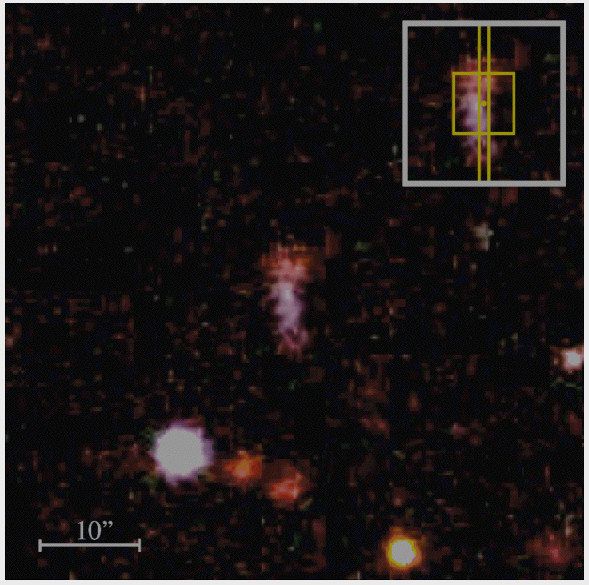




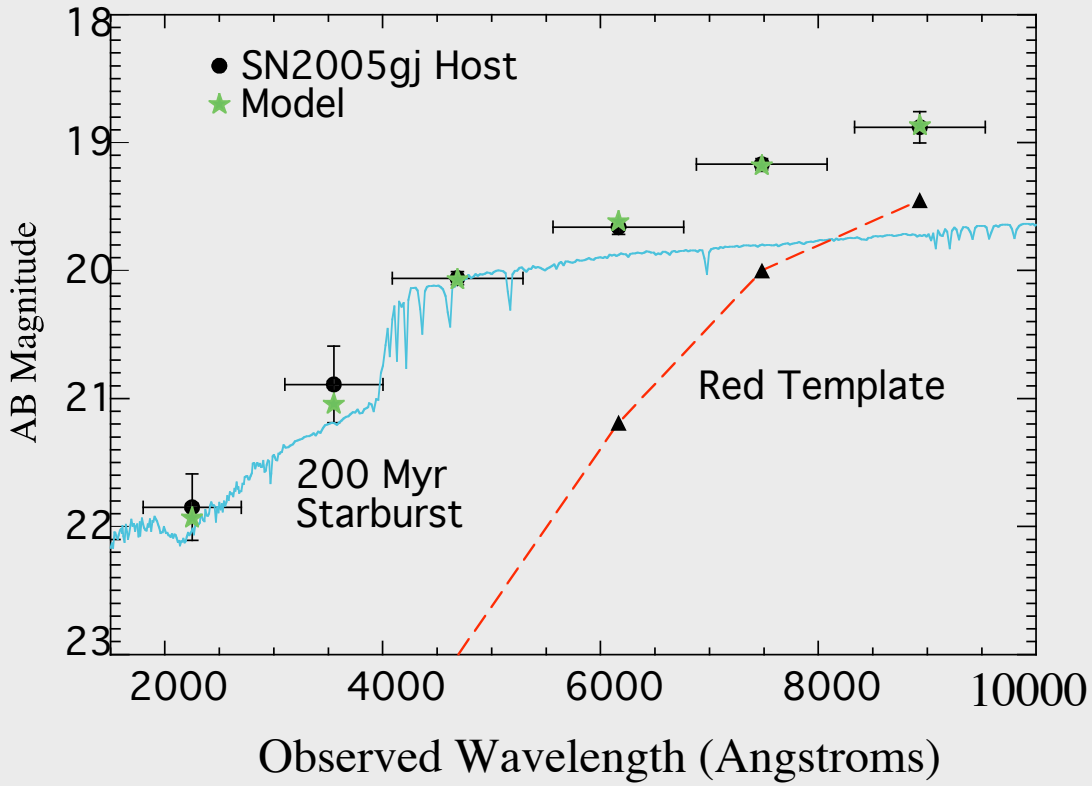
Aldering et al. 2006

Environmental Clues and Constraints

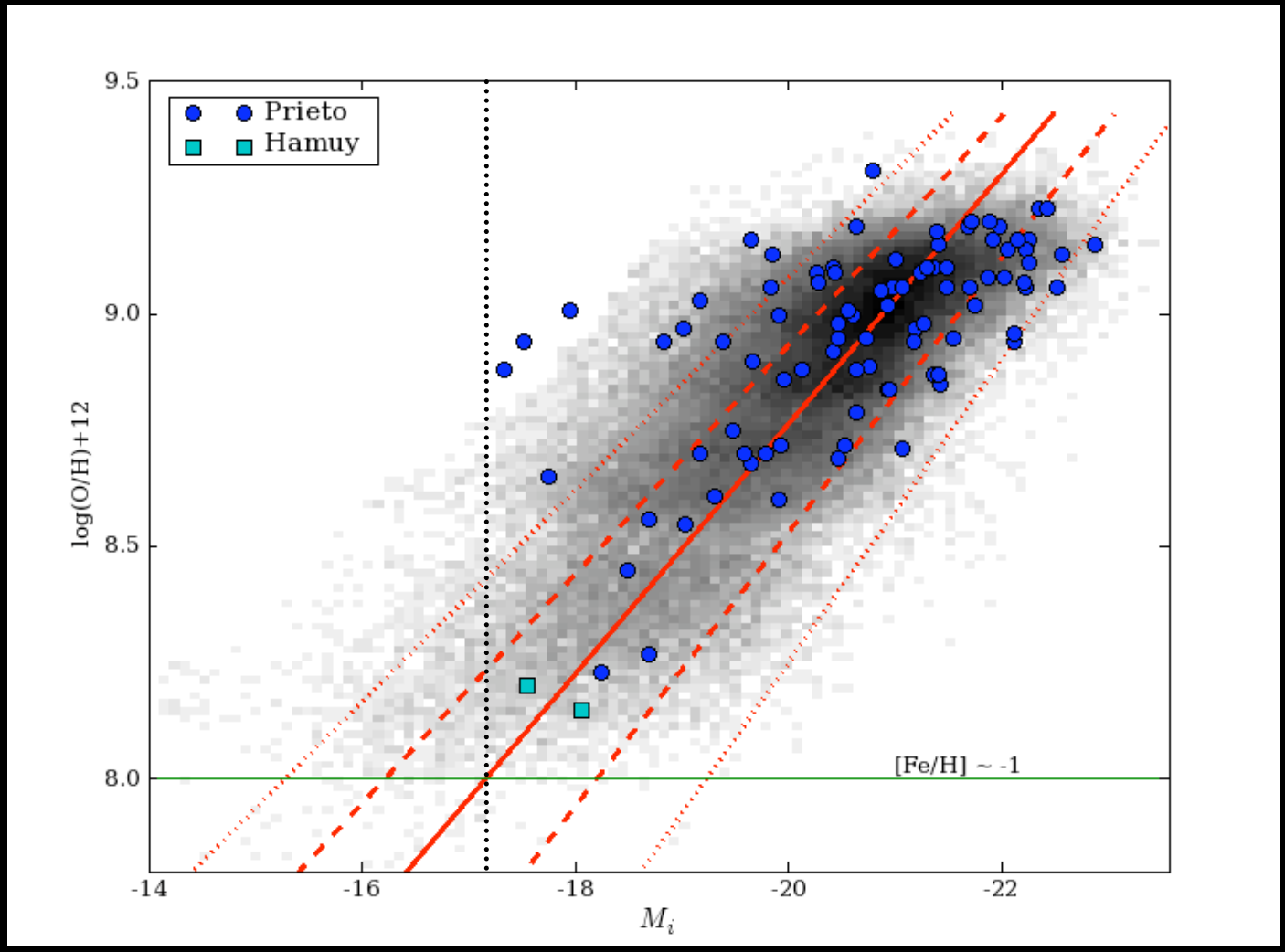
First SN Ia age estimate: 200 +/– 70 Myr (68% confidence)
Low metallicity: less than 1/3 solar (95% confidence)



Aldering et al. 2006



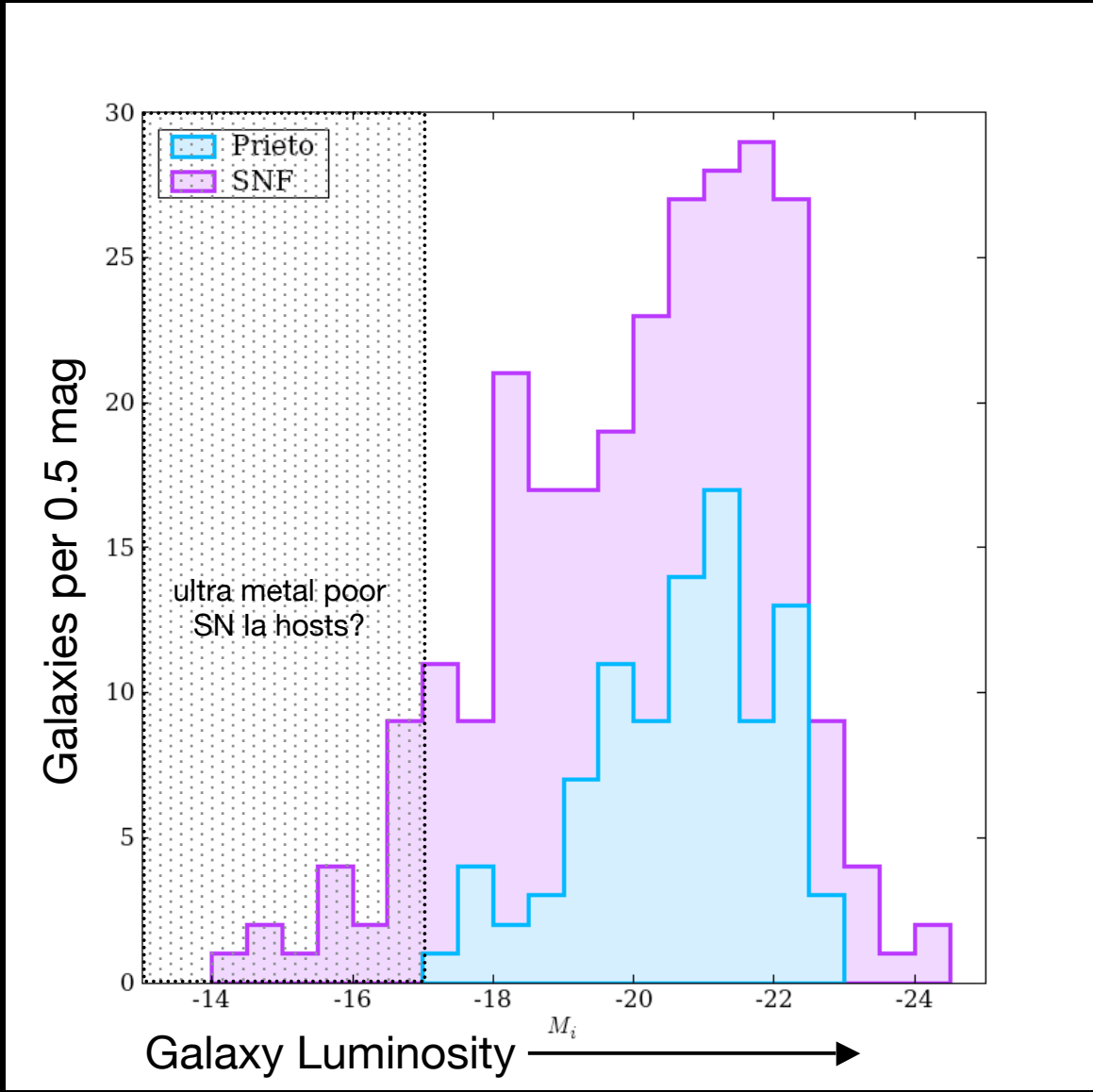
Environmental Clues and Constraints



Galaxy Metallicity

Galaxy Luminosity

Environmental Clues and Constraints



Summary

- To date we have 137 SNe Ia with a spectral time series.
- The SNIFS data pipeline is now producing lightcurves.
- We already have a great set of SNe Ia on the Hubble diagram!
- Palomar search has been very productive.
- SNIFS provides a unique and powerful capability.
- SNIFS follow-up is efficient & effective.
- Host galaxies studies underway offer complementary information.
- We've helped widen SN Ia parameter space
  (CSM, carbon confusion, different progenitor channels, etc.).